IMPROVING INTERCONTINENTAL BALLISTIC MISSILE MAINTENANCE SCHEDULING THROUGH THE USE OF LOCATION ANALYSIS METHODOLOGIES

THESIS

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Abstract

The events of September 11, 2001 raised concerns about our nation's ability to protect its citizens, structures, and resources from the mounting threat of terrorism. As a result, the United States has taken drastic measures to enhance security practices in many facets of our lives. Senior leaders have questioned whether mandated security levels used for nuclear weapons activities are sufficient to protect our nuclear assets from damage, destruction, or theft. These concerns have resulted in major changes to Department of Defense and Air Force security instructions. Security instruction supplements have increased the number of security personnel required during nuclear weapon activities and have reduced security response times to possible hostile events at ICBM launch facilities. In light of these security supplements, ICBM maintenance units must explore new methods for developing daily maintenance schedules to sustain current levels of weapon system readiness. This research seeks to provide missile maintainers with such a tool.

The problem of maximizing missile maintenance activities is modeled as a two-stage heuristic that utilizes maximal covering location problem techniques to produce feasible solutions. Maintenance activities are assigned to one of 18 maintenance categories. Each category is given specific weights according to mission impact, amount of pre-maintenance coordination required, and the published maintenance priority system. The first stage of the model seeks to identify which security umbrellas maximize the total weighted sum of all feasible maintenance activities that require security forces support. The only stage-one constraint is the number of supportable security umbrellas

available. The second stage of the model creates a maintenance schedule by maximizing the weighted sum of all maintenance activities at launch facilities that fall within the security umbrellas determined by stage one. Constraints for stage two include availability of maintenance teams, security personnel, and security force response times. The final model solution selects and schedules required maintenance at open holes and penetrated launch facilities that maximize the total weighted sum of all feasible maintenance events falling within the assigned security umbrellas. To complete the daily schedule, maintenance schedulers assign any unused maintenance teams to those maintenance activities not requiring security forces support.

Scheduling effectiveness is determined by comparing the research model solutions to the results of actual maintenance activities accomplished at Francis E. Warren AFB, WY, from May 1 through May 26, 2005. Additionally, sensitivity analysis is used demonstrate the effects of adjusting security force response times and the number of security umbrellas on the type and number of maintenance activities that can be performed. Missile maintenance and security forces managers can use this information to determine a feasible security combination that fulfills prescribed security requirements, while sustaining current weapon system readiness levels.

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IMPROVING INTERCONTINENTAL BALLISTIC MISSILE MAINTENANCE SCHEDULING THROUGH THE USE OF LOCATION ANALYSIS METHODOLOGIES

I. Introduction

Background

Since the early 1960's, the nuclear triad has served as the foundation of the United States' nuclear deterrent force. The nuclear triad comprises long-range bombers, Submarine-Launched Ballistic Missiles (SLBM), and land-based Intercontinental Ballistic Missiles (ICBM) (Trainor and Jain, 1999:1). Each element of the triad is geographically separated, utilizes different methods of weapons delivery, and is individually capable of devastating numerous enemy targets (Russell and Wirtz, 2002:1). Combining the strengths of these three separate nuclear weapons systems has not only provided the United States with strategic flexibility, but has also made it increasingly difficult for an enemy to exploit potential weaknesses of one individual system without fear of retaliation from the remaining systems. The United States' ability to maintain, protect, and employ this nuclear weapons infrastructure has effectively dissuaded nuclear attack for over 40 years.

In 2002, the composition of the nuclear triad was realigned to address changes in the post-Cold War political environment. The three components of the previous nuclear triad were combined with precision conventional weapons to form one leg of the new

"strategic triad." The remaining legs were reclassified as, "passive and active defenses and a revitalized defense infrastructure" (Russell and Wirtz, 2002:1). This new triad structure not only addresses the latest threat of rogue nations with potential nuclear capabilities, but also provides the United States with a variety of offensive and defensive options, both nuclear and conventional, should deterrence fail. In order for deterrence to remain effective, potential adversaries must be certain that the United States has the resolve and capacity to respond immediately to an attack. ICBMs serve as the long-range attack segment of this nuclear deterrent force.

The Minuteman III weapon system is the only remaining ICBM available to war planners. It is a three-staged, solid propellant missile that is designed to carry up to three independently targetable re-entry vehicles (Minot AFB, n.d.:5). The 500 Minuteman III missiles are dispersed among 3 Air Force bases: 200 missiles at Malmstrom AFB, Montana; 150 missiles at Minot AFB, North Dakota; and 150 missiles at F. E. Warren AFB, Wyoming. Each missile is "at least 3 nautical miles from any other [missile] and is situated in low population areas" (90 SW Public Affairs, 2001:6). The total area that encompasses all missiles of a base is called the missile complex. The combined area of the 3 existing missile complexes is approximately 44,600 square miles and extends across 5 states (Minuteman ICBM History, n.d.).

ICBMs are stored in unmanned, hardened, underground structures known as launch facilities (LF). Each LF is enclosed within a fence, which contains the launcher support building (LSB) and the launcher. The LSB contains equipment necessary to sustain the missile systems for extended periods of time. The launcher is made up of the launcher equipment room (LER) and the launch tube. The LER is a two-tiered facility

that surrounds the launch tube and contains missile security, environmental, and power systems. The missile is housed within the launch tube and is covered by a 110-ton launcher closure door (90 SW Public Affairs, 2001:7), which protects the missile from the environment and the effects of nuclear detonation. Each LF is connected to a launch control center (LCC) via a hardened, underground cabling system.

The LCC is an underground capsule that contains the two missile combat crew officers who are responsible for launching the ICBMs. The two-person crew monitors security and missile status of 10 LFs around the clock, rotating shifts with another crew after 24 hours of duty. Above the LCC is a building known as the missile alert facility (MAF). The MAF serves as a staging point for security forces teams deployed to the missile complex, as well as an area away from the main base where maintenance personnel can Remain Over Night (RON) when the mission dictates. One MAF, one LCC, and ten LFs make up a flight area; five flights make up a squadron. F. E. Warren AFB has three Minuteman III missile squadrons: the 319th, 320th, and 321st Missile Squadrons, each responsible for 50 ICBMs. In order to identify individual facilities, each MAF and LF is assigned an alphanumeric character. At F. E. Warren AFB, the letters A through O designate which flight area each facility is assigned; the numbers 01 through 11 identify individual facilities within that flight area, 01 designating the MAF and 02 through 11 representing the LFs.

Air Force Space Command Instruction (AFSPCI) 21-114 outlines an ordered priority system to dictate precedence for maintenance activities performed for ICBMs. Appendix A includes the priority designator attachment from this instruction. Maintenance activities are rank ordered from priority one through priority nine: priority-

one maintenance activities are the most crucial, often requiring immediate repair or replacement of critical equipment to maintain weapon system and personnel safety; priority-nine activities are deferred discrepancies, which are generally minor repairs that have no impact on the missile operation. When priority-one circumstances arise, standby maintenance teams normally dispatch to correct the situation immediately. To ensure immediate response capabilities, standby priority-one teams must be readily available and have the appropriate number of security personnel assigned solely for this purpose. In essence, at least one maintenance team and its security forces members are removed from the pool of teams available for dispatch, in the event that a priority-one situation arises. Missile maintenance schedulers must juggle security personnel constraints to maintain the highest missile alert rate possible, while still accomplishing the lower-priority tasks that are necessary to keep the missile infrastructure intact and support systems functioning properly.

Periodic maintenance work centers are responsible for performing structural maintenance, as well as routine support system maintenance required to keep these systems functioning properly. Though these tasks seem menial when compared to higher-priority maintenance tasks, periodic maintenance is critical to the survivability of the entire weapon system. Periodic maintenance activities are generally categorized as priority-six maintenance activities; as such, these maintenance activities have historically been cancelled in order to release security personnel for higher-priority maintenance. With changing security requirements, periodic maintenance activities will continue to compete with higher-priority maintenance activities for security resources.

Maintaining a Minuteman III missile requires the joint efforts of missile maintenance and security forces personnel. Maintenance tasks are divided into several categories, each having particular security requirements and differing levels of access to the launch facility. Any maintenance task that requires the launcher closure door to be opened while a reentry system (RS) is present is called an open hole. An open hole occurs any time major components on the ICBM or launcher closure door require repair or replacement. Open holes require a specific number of security personnel to be assigned solely to that launch facility to protect the exposed weapon from potential enemy attack or acquisition. Maintenance activities that require access to the launcher when an RS is present, but do not require the launcher closure door to be opened, constitute a penetrated launch facility. A penetrated launch facility does not directly expose the missile, but does provide maintenance personnel access to classified system components and critical support equipment contained within the LER. Security escort teams (SETS) are assigned to the maintenance team to protect the launch facility at ground level, while additional roaming security teams, called Missile Support Fire Teams (MSFTS), are available to respond within a predetermined period of time should a hostile situation arise. Finally, maintenance activities that only require access to the LSB or the ground level of the launch facility do not require SETS or MSFTS, as access is not provided to critical weapon system components or equipment.

The terrorist acts of September 11, 2001 have raised concerns as to whether current mandated levels of security personnel used for maintenance dispatches are sufficient to protect all ICBMs from damage, destruction, or theft. These concerns have resulted in major changes to Department of Defense and Air Force security instructions,

which now require the presence of additional security personnel during weapon system maintenance activities within the missile complex. Additionally, recent regulation changes have decreased the security forces' response times to penetrated missile launch facilities. Dawson (2005) specifically addressed the decreased response times by developing an optimization method specifically for security forces schedulers. Currently, security forces personnel are staged at 1 or more of the 15 Minuteman III missile alert facilities. However, the method developed by Dawson (2005) considers establishing security team staging points at the 15 missile alert facilities, the 150 Minuteman III launch facilities, and 68 additional locations, and positions each security "umbrella" based on missile maintenance activities scheduled for that day. A security umbrella is defined as a geographical cluster of launch facilities that fall within a specified travel time of the security staging area. The size of the security umbrella determines how many launch facilities can be effectively protected by assigned security forces personnel. With a finite number of security fire teams and SETS available each day, only a limited number of maintenance activities can be performed. In one approach, Dawson (2005) attempted to minimize the maximum security force response times while accomplishing all missile maintenance tasks built into the daily schedule. This research is a continuation of the Dawson (2005) effort, but focuses more on the maintenance scheduling aspect of missile maintenance.

Problem Statement

Security waivers are currently in place that enable ICBM managers to offset the initial shock of increased security requirements; however, waivers only serve as a

temporary solution to the looming, more permanent changes that must occur with maintenance scheduling practices to properly sustain our land-based nuclear deterrent force. Therefore, missile maintenance managers need a method for enhancing maintenance scheduling methods that can compensate for the limited number of security personnel available, while attempting to maintain current levels of weapons system integrity. Solutions to this problem can be provided by analyzing maintenance scheduling practices currently employed at F. E. Warren AFB, and then developing a scheduling tool to supplement current scheduling procedures. This would allow logistics managers to work with security forces managers to maximize the sum of weighted maintenance activities performed, given the security forces personnel constraints.

Research Question

This research seeks to answer the following question: How can current ICBM maintenance scheduling methods be enhanced to compensate for given security requirements while sustaining prescribed readiness levels? This question addresses the current operating environment, and is most concerned with security forces manpower limitations and security requirements that detrimentally impact the maintenance organization's ability to maximize maintenance activities. The basis for answering this primary question is found by answering five investigative questions.

Investigative Questions.

1. How can current ICBM maintenance scheduling methods be exploited to maximize the number of daily maintenance activities performed?

2. What types of facility location methodologies have been utilized in previous research and which ones best represent the problem being researched?

3. How can missile maintenance activities be enhanced to maximize use of personnel and/or reduce maintenance cancellations while taking into account the best use of available security personnel?

4. How do experimental results of improved scheduling techniques compare to historical results?

5. What effects will changing the various missile security requirements have on the scheduling of daily missile maintenance activities?

Scope and Limitations

This thesis utilizes unclassified maintenance and security forces data collected for the 150 Minuteman III LFs at F. E. Warren AFB, WY, for May 1 through May 26, 2005. During the month of May 2005, the launch coding information was changed for missiles at 100 launch facilities in 2 missile squadrons. Code changes are scheduled to occur within each missile squadron once per year and require a large number of equipment and manpower resources. Because code changes are special events that occur infrequently, these maintenance activities are not considered in this thesis. The Peacekeeper weapon system was still on alert during this analysis period, but Peacekeeper launch facilities and required security personnel are omitted from the study, as the weapon system will be fully deactivated by the time this research is completed. Due to current historical record file plan requirements and Unclassified Controlled Nuclear Information (UCNI) classification of the daily missile maintenance schedules, this research relies strictly on

unclassified data provided by the 90th Maintenance Operations Squadron (90 MOS) scheduling and Missile Maintenance Operations Center (MMOC) sections. The findings and conclusions of this thesis are applicable only to F. E. Warren AFB based upon the missile complex configuration and base-specific maintenance data collected. However, it is hoped that the results are generalizeable to the missile units at Malmstrom AFB and Minot AFB. Differing security requirements and missile maintenance scheduling methodologies at the other missile bases may impact the effectiveness of employing the developed heuristic at the remaining missile maintenance units. Therefore, although Malmstrom AFB and Minot AFB share similar characteristics to F. E. Warren AFB, the variables within the research model, the research findings, and conclusions must be modified specifically to those missile wings' environments before the research model can be effectively employed.

Other limitations include the flexibility of security forces personnel positioning within the missile complex. At present, security forces personnel are staged at 1 or more of the 15 Minuteman III missile alert facilities. As such, the model developed in this research only considers centering security umbrellas at these locations. However, if units choose to consider additional staging areas, the research model must be altered to consider this change in policy. Finally, the model only considers information available to this researcher at the time of data collection, and the solutions produced and conclusions provided only consider this data.

Overview

This chapter provides the motivation for developing a missile maintenance scheduling tool to optimize maintenance activities performed daily at F. E. Warren AFB, Wyoming. Pertinent background information on the Minuteman III weapon system, organizational structure, and maintenance procedures is provided to familiarize the reader with ICBM practices. Overall, the intent of the research is to provide logistics managers with a tool for developing cluster-oriented maintenance schedules that maximize the weighted sum of maintenance tasks performed, while working within the security and maintenance manpower constraints.

Chapter II defines key terms essential to understanding the missile maintenance scheduling problem. The chapter reviews current Department of Defense and Air Force directives relating to ICBM maintenance and security. Also, previous research performed in the area of ICBM maintenance and security scheduling is identified. A history of location analysis and the maximal covering location problem is provided, and finally, a description of optimization models and heuristics is offered.

Chapter III describes the methodology of the thesis. It explains the data collection process, the selection and development of the experimental model, and provides the specific mathematical formulations of the model to be analyzed in Chapter IV.

Chapter IV discusses the results of the two-stage heuristic model, comparing the outputs to actual historical data. Results of model sensitivity analysis are provided, as well as a post analysis, which demonstrates the effects of distance matrix changes on model outputs. These comparisons form the basis for conclusions in Chapter V.

Chapter V discusses the conclusions and inferences that can be drawn from the model results. Model limitations are discussed and recommendations for model implementation are provided. Finally, suggestions for future research possibilities are presented.

II. Literature Review

Introduction

In this chapter, several key terms are defined that are essential to achieving a better understanding of the research problem. Next, a review of current Department of Defense (DoD) directives, Air Force Instructions (AFI), and Air Force Space Command Instructions (AFSPCI) relating to the Intercontinental Ballistic Missile (ICBM) maintenance and security forces activities is provided. Additionally, previous research in the area of ICBM maintenance and security forces scheduling is summarized, and existing ICBM maintenance and security forces scheduling practices at F. E. Warren AFB, WY are discussed. A brief history of location analysis is also offered, as well as an overview of the maximal covering location problem methodology, which forms the basis for the scheduling model developed in this thesis. Finally, characteristics of optimization models and heuristics are discussed.

Definitions

There are many key words and phrases used throughout this chapter that are specific to the ICBM weapons system and its infrastructure. It is important for readers to recognize some of the basic terminology, as it will help to develop a better understanding of the components that characterize the missile maintenance scheduling problem. Several of these essential terms are defined in Table 1.

Table 1. Key Terms and Definitions

Term	Definition
Intercontinental Ballistic Missile (ICBM)	Long-range, land-based nuclear missiles assigned to the Air Force inventory
Launch Control Center (LCC)	Underground capsule below MAF which contains the missile combat crew; is connected to LFs via underground cabling system
Launch Facility (LF)	A remote, underground facility in which alert ICBMs are stored; contains the topside structures, LERs, and LSB.
Launch Tube	Hardened cylinder which holds the missile
Launcher Closure Door	110-ton door that covers the launch tube; protects missile from environment and possible enemy nuclear detonation
Launcher Equipment Room (LER)	Below-grade, two-tiered facility that surrounds the launch tube; contains missile security, environmental, and power systems
Launcher Support Building (LSB)	Below-grade facility that contains equipment necessary to sustain missile for extended periods of time
Missile Complex	The total area that encompasses all missiles of a base; i.e. the F. E. Warren AFB missile complex contains 150 missiles within a 12,600 square mile area
Missile Alert Facility (MAF)	Staging area for security personnel, location of LCC, area for teams Remaining Over Night (RON), and focal point for security umbrellas
Open Hole	"A LF with an open launcher closure door and an operational reentry system (AFSPCI 21-114, 2003:20)
Penetrated LF	"A LF where the A and B circuit combinations have been passed" (AFSCPI 21-114, 2003:20); permits access to missile, operating systems, and support equipment
Re-entry System (RS)	Portion of the ICBM that contains the nuclear warheads and systems associated with transporting the payload to its target.
Security Escort Teams (SETS)	Security team that accompanies missile maintenance teams to an LF; protects the topside of the LF while the maintenance teams accomplish the assigned work tasks.

DoD and Air Force Nuclear Weapons Guidance

There are several documents utilized by missile maintenance managers and security forces personnel that dictate the operating environment for ICBMs. DoD Directive S-5210.41M (Draft) is the governing instruction for all nuclear weapons security procedures. DoD policy is to "protect nuclear weapons from loss, theft, sabotage, unauthorized use, and unauthorized or accidental damage or destruction" (DoD 5210.41M, n.d.). This directive defines the minimum number and type of security personnel required to perform specific maintenance activities, such as open holes and

penetrated launch facilities. It also dictates the maximum security force response times for open holes and unmanned launch facilities. Finally, this regulation provides specific arming requirements for security forces teams deployed to the missile complex.

AFSPCI 31-1101 is concerned with the protection of the Minuteman III weapon system and uses the security guidelines defined in the DoD directive to establish security requirements specific to the land-based ICBM force. This instruction provides detailed entry control procedures for launch facilities and missile alert facilities, procedures for securing sites experiencing problems with physical security systems, and procedures for responding to potential security violations. Some specific guidelines include the requirement of a security escort team (SET) to accompany a missile maintenance team that must penetrate a launch facility to perform a maintenance task. It also dictates the number of security fire teams deployed to the missile complexes of each missile base. A fire team is a heavily armed security team that responds to potential threats at missile alert facilities, as well as manned and unmanned launch facilities. The number of SETS and other security personnel available for duty establishes the security personnel constraints for the scheduling model developed in this thesis.

AFI 21-114 establishes procedures for maintaining the Minuteman III weapon system. It assigns specific maintenance and support responsibilities to each level of supervision within the chain of command, from HQ USAF down to the Maintenance Group commanders at each missile base. This instruction specifies that managers will support Operational Plan (OPLAN) 8044 by developing policy and procedures that "achieve the most efficient use of manpower and fiscal resources, safety, surety, readiness, and maintenance productivity" (AFI 21-114, 2000:4). OPLAN 8044 is the

"name of the U.S. strategic nuclear war plan SIOP (Single Integrated Operational Plan)" (Federation of American Scientists, n.d.). In order to support OPLAN 8044, Maintenance Group commanders must "ensure a safe, timely response to discrepancies at [LFs, MAFs], and support facilities, placing extra emphasis towards clearing non-mission capable and partial-mission capable discrepancies" (AFI 21-114, 2000:4).

AFSPCI 21-114 establishes procedures for maintaining the Minuteman III weapon system, but focuses on unit-level responsibilities, down to the work center managers. This instruction provides a detailed maintenance priority system, which is used to develop daily maintenance schedules. The priority designators are included in Appendix A. The instruction also provides guidelines as to when specific maintenance activities can be performed. Additionally, AFSPCI 21-114 addresses the requirement to "develop, coordinate, and publish maintenance schedules," and specifically, "coordinate the commitment of wing/group resources via the daily maintenance plan" (AFSPCI 21-114, 2003:27). This portion of the instruction is of particular interest for this research, as it implies the "coordinated" efforts of maintenance and security forces schedulers, the primary workers needed to schedule missile maintenance efficiently. This instruction is the main document used by the missile managers at each base, as it establishes the operating guidelines for all unit-level missile maintenance activities.

Previous ICBM Maintenance and Security Initiatives

Several attempts have been made to enhance the missile maintenance and security forces scheduling practices. In the 1999 paper titled, *Proposed Concept of Operations for Umbrella Security and Clustering of Maintenance Ops*, Captain Jack Seaberg of the

790th Missile Security Forces Squadron (MSFS) proposed to create security "umbrellas" throughout the F. E. Warren AFB missile complex. His intent was to geographically cluster all missile maintenance activities requiring launch facility penetration within designated security "umbrellas." The security umbrella(s) would be centered upon the 20 missile alert facilities, 15 Minuteman III and 5 Peacekeeper, and cover all launch facilities located within 1 hour of the missile alert facility. By using these security umbrellas, it was suggested that security forces teams could better protect missile sites from potential hostile activities because the size of the security teams' area of responsibility is reduced. Under this concept, up to two "events" could be supported daily, Monday through Thursday only, given security manpower constraints. An event is defined as a security umbrella, convoy, or maintenance activity requiring an open launcher closure door. The proposal further states, "Two open launcher activities could also be scheduled as long as one (and preferably both) was underneath the security umbrellas" (Seaberg, 1999:2). The proposal also offered that maintenance activities at any penetrated launch facility would be performed daily between 0700-1700, with the launch facility closed and site physical security alarms reset no later than 1900. Weekend maintenance activities would be limited to only one event. Captain Seaberg's recommendations were reviewed by base leadership and later tested. During these tests, missile maintenance managers found that the security umbrella positioning was not driven by maintenance requirements, but instead, maintenance activities revolved around the pre-positioned security forces teams. Instead of enhancing daily maintenance schedule flexibility, the umbrella concept actually restricted maintenance activities to

these prescribed security umbrellas. As a result, the umbrella concept was not implemented.

Captain Dennis Maynard, an Air Force Institute of Technology student, performed a case study in December 2003 on the Periodic Maintenance Team (PMT) schedule for 341st Maintenance Squadron at Malmstrom AFB, Montana. In this case study, he proposed to adjust the PMT annual maintenance schedule so that the launch facilities furthest from the support base would be scheduled during the fair weather months, instead of the during winter months. Two linear programming (LP) optimization programs were developed using Microsoft Excel® with the Large Scale LP Solver Engine™ plug-in. The first model objective was to "minimize the total winter driving time", while the second model objective was to "minimize the total winter driving distance" (Maynard, 2003:3). Captain Maynard compared the model solutions against the existing PMT annual maintenance schedule and concluded that although both models produced better solutions than the existing schedule, the model that minimized total travel time proved to be the superior model.

During an early 2004 presentation to General Lord, the commander of Air Force Space Command, Captain Jerome James and the 341st Maintenance Group proposed another method of enhancing security during missile maintenance operations. They offered that the number of required SETS could be decreased if the Reentry System (RS) was removed from the missile prior to annual periodic maintenance activities. In doing so, all annual, periodic launch facility maintenance could be accomplished within an established time period without the presence of security personnel. This would not only eliminate the potential for cancelled periodic maintenance activities due to security

manpower shortfalls, but would also release much needed security personnel for higher-priority maintenance activities. Unfortunately, the disadvantages of the proposal far outweighed the prospective benefits. Such an effort would require unnecessary exposure of the RS to potential threats, would likely result in an increase in overtime pay for the civilian employees, and would ultimately result in lost maintenance days due to large number of security resources consumed while transporting the RS. The detrimental impact to the ICBM mission dwarfed any potential gains offered, so the proposal was never implemented.

In January 2005, Major Jack Seaberg submitted a revised umbrella security concept proposal to the 90th Space Wing and the 20th Air Force (20 AF) leadership for reconsideration. This proposal is much like the previous version, but now addresses the post-September 11 operating environment. In his opening remarks, Major Seaberg states:

> The purpose of this plan is to provide 90 SW personnel with a guideline for increased security of resources through centralized positioning of missile field maintenance activities and positioning of Missile Support Fire Teams to address security requirements outlined in the new [DoD 5210.41M]. (Seaberg, 2005:1)

In this updated proposal, all periodic maintenance would be performed Monday through Thursday, while maintenance activities on Friday through Sunday would be limited to two penetrated launch facilities daily. Maintenance activities requiring launch facility penetration would be limited to daylight hours, unless waived by the base commander. As with the previous proposal, a maximum of two events would be covered daily; however, additional latitude would be provided for supporting a separate “mini-umbrella” outside of the established security umbrella(s). A “mini-umbrella” is a special situation involving unscheduled priority-one or priority-two maintenance activities, requiring

approval by the maintenance group and base commanders. Major Seaberg provides a list of other considerations, including the effects of cluster maintenance on missile combat crews and flight security controllers. Discussion concerning helicopter support, specific security force team composition, and emergency response activities are also included, but are not discussed because they are beyond the scope of this thesis. Major Seaberg's proposal has been submitted to 20 AF for approval and possible implementation.

In a separate concept of operations titled, *Background Paper on 790 MSFS Fire Team Reconfiguration Proposal,* Major Seaberg recommends a change in Missile Support Fire Team (MSFT) composition to enhance security capabilities of the 790th Missile Security Forces Squadron. This change decreases the number of personnel assigned to a MSFT by one security member. Doing so releases enough security personnel to form an additional MSFT. The availability of an additional MSFT offers the potential of an additional "mini-umbrella," as discussed in the previous paragraph. Major Seaberg states, "by creatively using assigned manpower, Fire Teams can provide greater detection, deterrence, and response capabilities for priority-one resources…" (Seaberg, 2005:1). This proposal has also been submitted to 20 AF for consideration and possible implementation.

In addition, Dawson (2005) developed a Microsoft Excel®-based scheduling tool that establishes security umbrella focal points at locations outside the normal 15 Minuteman III missile alert facilities proposed by Major Jack Seaberg. This tool uses an array of facility location optimization techniques to position security fire teams based on the daily missile maintenance schedule. The outputs of the scheduling tool provide results that closely parallel Major Seaberg's umbrella security concept. The research

model offers the flexibility of staging security fire teams at any of the 15 missile alert facilities, 150 launch facilities, or 68 additional strategic locations throughout the missile complex. Additionally, it offers security forces schedulers the option to place security fire teams based on several different objectives: maximizing the number of launch facilities covered by the security umbrella; minimizing total security team travel time; or minimizing longest travel time. (Dawson, 2005) Senior leaders at F. E. Warren AFB have discussed performing a 120-day test of Dawson (2005) scheduling tool, but a date for this test has not been established.

Current Scheduling Practices

As per AFSPCI 21-114, the 90th Maintenance Operation Squadron (90 MOS) is responsible for the development, coordination, and publishing of the daily missile maintenance schedule. The scheduling section personnel build the daily schedule one day prior to the day maintenance tasks are performed. The long-term maintenance forecast developed by the missile maintenance scheduling section dictates which life-extension programs, weapon system upgrades, and depot-level maintenance activities must be performed. These programmed activities are combined with other outstanding maintenance work orders and assigned to the schedule according to the priority system dictated in AFSPCI 21-114.

Each individual maintenance section provides team availability information to the scheduling section no later than the morning that the schedule is being developed (Boje, 2005). Once all section inputs are received, schedulers run a priority-one through priority-four work order listing from which to select launch facilities for the maintenance

schedule. The work order listing is derived from data stored within the Improved Missile Maintenance Program (IMMP), the ICBM maintenance team tracking and data collection software. Maintenance teams are assigned to a launch facility based on off-alert status, previously scheduled long-term program maintenance, priority of the work orders loaded in IMMP, and the availability of SETS. Once each team is assigned to a launch facility, the assignment information is loaded into the IMMP system. All additional work orders that the scheduled maintenance team is capable of performing at the appointed launch facility are also assigned as part of the team's work package. All work orders completed are debriefed, while incomplete work orders remain in IMMP for future maintenance dispatches. After all teams are loaded in the system, the schedulers use the security umbrella worksheets to visually determine which umbrella(s) best cover all maintenance activities being performed. Security umbrella information is relayed to the security forces schedulers for further planning. The resulting draft schedule is later coordinated with security forces schedulers and individual maintenance sections during the afternoon scheduling meeting (Boje, 2005).

Section missile maintenance schedulers, security forces schedulers, and the 90 MOS scheduling representatives coordinate throughout the day on the draft schedule, but final coordination actually occurs during the afternoon scheduling meeting. Security forces schedulers provide changes to the number of SETS available for the following day. The schedule is fine-tuned to account for any changes in available SETS. Higher-priority and time-restricted maintenance activities are assigned the required number of SETS until either all of the security personnel or all maintenance teams are exhausted. Once all SETS are used, the lower-priority maintenance activities that remain in the draft

maintenance schedule are either altered or removed completely from the schedule. Unscheduled tasks must then be rescheduled for a later date. Immediately following the meeting, the schedule is finalized and published (Boje, 2005).

The daily schedule is subject to change even after the finalized copy has been distributed. Unscheduled, high-priority maintenance situations arise regularly, which require security and maintenance resources to be shifted from previously scheduled, lower-priority tasks. Additionally, unexpected changes in personnel or equipment availability can occur, which also requires the daily schedule to be adjusted. The Missile Maintenance Operations Center (MMOC) is responsible for coordinating unscheduled maintenance activities that occur outside normal duty hours, as well as weekends and holidays. The MMOC is a 24 hour, 7 days per week operation whose mission is to monitor status of all missiles within the base missile complex around the clock. When an unscheduled, high-priority situation arises, or unforeseen personnel and resource availability issues occur, MMOC controllers immediately notify the group commander and request authority to make schedule changes. Once approved, all changes are coordinated through security forces and maintenance section supervisors, who in turn, notify the affected teams. Any scheduled activities that are cancelled are then reconsidered for a later date.

Incorporating Location Analysis into Maintenance Scheduling

As the name implies, facility location methodologies are typically used to assist decision makers in selecting locations to place new facilities. Usually, to maximize the effectiveness of a facility, it must be located in an area central to a given population

center. So how do facility location methodologies relate specifically to the scheduling of ICBM maintenance activities? Let us first summarize the environment in which missile maintenance and security forces personnel operate.

Maintenance of the Minuteman III weapon system requires maintenance and security teams to travel to 1 or more of 150 launch facilities, all of which are geographically isolated from major population centers. Travel time from F. E. Warren AFB, the main support base, to the launch facilities can range from less than 25 minutes to over 2.5 hours (90 SW, n.d.:B4). By regulation, teams are limited to a 16-hour timeline, which begins as soon as a team arrives at the F. E. Warren AFB work center to make travel preparations, and ends once all post-maintenance actions are completed--debrief, vehicle/equipment turn-in, etc., or once the team arrives at one of the 15 missile alert facilities dispersed throughout the 12,600 square-mile missile complex. Each missile alert facility serves as the hub of one security umbrella, allowing for up to 15 total security umbrellas. Missile security forces personnel support two security umbrellas per day, which have a maximum coverage radius of 60-minutes travel time from the missile alert facility. Missile alert facilities have already been built, so their locations are fixed. However, the hub of supported security umbrellas can shift between missile alert facilities daily, depending on which area(s) of the missile complex the launch facility maintenance activities are concentrated. Open hole maintenance and maintenance actions requiring penetration of the launch facility must fall within at least one security umbrella, or maintenance cannot be performed. As such, schedulers must try to geographically cluster maintenance activities within these two security umbrellas to forego maintenance cancellations. Previous military research on the topic of missile

maintenance scheduling has indicated that this particular type of problem can be well defined as a facility location problem (Dawson, 2005).

Specific components from the previous missile maintenance scheduling environment summary can be used to form an objective function for this problem: *select two security umbrellas, each with a maximum 60-minute response radius, which will allow for the greatest amount of scheduled maintenance activities to be covered.* This objective can be further restated as a facility location objective function: *locate two <u>facilities</u> that will cover the greatest number of maintenance <u>demand nodes</u> within a 60-minute radius of the facility*. As the stated objective function implies, not all demand nodes can be covered by the two selected facilities. This limitation is key to selecting which facility location methodology best fits the missile maintenance scheduling problem.

Early Contributions to Location Analysis

Location analysis has been a critical factor in decision making since the beginning of mankind. Prehistoric people chose areas to establish temporary shelters that best provided for their basic survival needs. As humans became more advanced, temporary shelters gradually became more permanent. Permanent domiciles led to establishment of communities, social networks, and eventual economic interactions between civilizations. Over time, facility location decision criteria have expanded well beyond the fulfillment of basic survival elements, which are now considered as implied prerequisites. “Critical success factors,” such as labor productivity, total costs, per capita income, and proximity to markets, have now come to the forefront, shifting decision-making criteria from those

of basic human survival, to factors that "maximize the benefit of location to the firm" (Heizer & Render, 2004:302-307).

In the book, *Facility Location: Applications and Theory*, Drezner and Hamacher provide a thorough review of literature pertaining to the development of facility location models. Although the early history of facility location models is uncertain, researchers agree that the first model appeared sometime during the 1600's. The original facility location model dealt with "the problem of finding the spatial median, (the minisum Euclidean distance point)" (Drezner & Hamacher, 2002:3). It was not until the early twentieth century that researchers found applications to the enormous number of theories, models, and generalizations that have been developed since the inception of the first location analysis model. Of the many pioneers of location analysis, Alfred Weber has been considered as one of the key contributors to modern day facility location analysis, with his development of Industrial Location Theory (Friedrich, 1929).

One of the early predecessors to Weber was a German farmer and economist, J.H. Von Thunen, who "was the first to develop a basic analytical model of the relationships between markets, production, and distance" (Hofstra University, n.d.). In his 1826 model of agricultural land use, Von Thunen suggested that four rings of agricultural production would develop around a central market. The production of perishable products, such as fruits, vegetables, and dairy products, would form a ring closest to the market center. Lumbering activities would form the second ring, as wood was used heavily as both fuel and building materials, and was difficult to haul. Grain production was performed in the third ring, since grain was easier to transport and lasted much longer than products produced within the first ring. Livestock production took

place in the fourth ring, since animals were able to transport themselves to the city. All areas outside the fourth ring were considered to be too far from the city to develop agriculturally. Land closest to the central market was obviously more expensive due to market accessibility. To maximize profits, farmers had to select a location to establish business that created a balance between property costs, transportation costs, and production costs. Though the model was based on assumptions of market isolation, a level landscape throughout the area, and undeveloped transportation routes, the basic concepts of Von Thunen's early mathematical model demonstrated the importance of location selection on business owner profitability (Hofstra University, n.d.).

German economist Carl Wilhelm Freidrich Launhardt was another early contributor to the study of location theory. In his book, *Mathematical Principles of Economics* (1885), "Launhardt applied integral calculus to derive the consumer's surplus of a decrease in the freight rate for each consumer at a market point and for all consumers in the whole market area" (Shieh, 2005:1). His theory expanded on Von Thunen's agricultural model and "assessed the effect of a reduction of the freight rate on what he called 'the savings on the price of goods [that] benefits the customer'; i.e. the consumer's surplus" (Shieh, 2005:2). In essence, this model demonstrated the effects of transportation price changes on the quantity of product demanded by customers located at various distances from the central firm. Additionally, Launhardt's mathematical formulations demonstrated how various changes in transportation costs and quantity of product demanded by the customer affected the overall product costs to the customer. As with Von Thunen's model, the consumer's surplus model demonstrated the effects of facility location and management decisions on business profitability.

In 1909, Alfred Weber, another German economist, published the book entitled *Uber den Standort der Industrie,* or the *Theory of the Location of Industries*, which was translated into English by C.J. Friedrich in 1929. Weber's model sought to discover the optimal placement of an industry where transportation costs of raw materials and finished products, as well as labor costs, were minimized (Freidrich, 1929). His theory analyzed three key factors:

> 1. *Material Index*: locating the optimal industry location based distance costs and the ratio of weight of raw material and finished goods.
> 2. *Labor*: transportation distances may be increased if lower cost labor is available.
> 3. *Agglomeration and deglomeration*: spatial clustering or declustering of industries for maximum benefit, based on sufficient demand. (Fearon, n.d.)

The "material index" factor considered two types of activities. A "weight-gaining" activity determined industry location when the weight of the finished product was greater than raw material weight. A "weight-losing" activity determined industry location when the weight of raw materials was more than that of the finished product. Since transportation costs were largely determined by distance traveled and material weight, industry location was greatly affected by this factor. The "labor" factor considered the availability of low-cost laborers when determining industry location. Industries requiring unskilled labor could justify increasing distance, which increased transportation costs, if the realized labor cost savings was sufficient. Agglomeration is the act of concentrating firms within a relatively small area. This occurs when a sufficient level of demand is available to justify industry concentration within an area. Deglomeration occurs when diseconomies of scale have been reached due to over concentration of industry, often requiring facilities to relocate in order to remain productive. The combination of these

factors was used to locate the optimal location for an industry. Although the Weber Model only considered a single objective function, located a single facility, and assumed that a linear production relationship existed, its contribution to modern day location analysis methodologies is undisputed.

Modern Facility Location Methodologies

Since the inception of the Weber Model, numerous variations of the facility location model have been developed. Though all have the common objective of locating facilities, differing approaches, decision variables and constraints have made it impossible to develop one model that can solve every problem. In the paper, *Discrete Network Location Models*, the authors "provide eight basic facility location models, including the set covering, maximal covering, p-center, p-dispersion, p-median, fixed charge, hub, and maxisum" (Current et al, 2002:86). In each model, the geographic area under consideration, the candidate facility locations, and demand nodes are provided. The goal for each model is to maximize or minimize the objective function. "Distance or some measure more or less functionally related to distance (e. g. , travel time or cost, demand satisfaction) is fundamental to such problems" (Current et al, 2002:86).

The set covering location problem (SCLP) objective "identifies the minimal number and location of facilities, which ensures that no demand point will be farther than the maximal service distance from a facility" (Church & ReVelle, 1974:102). As is implied, all demand must be covered by the selected facilities. However, no constraint is placed on the number facilities to be located, so theoretically, an infinite number of facilities could be selected to cover all demand nodes. If this category of facility location

problem were applied to the missile maintenance scheduling problem, the algorithm would attempt to schedule every possible maintenance activity, given the manpower constraints. The set covering problem would be ideal to maximize the amount of maintenance performed, but in many instances, would require the availability of more than two security umbrellas, making this problem inappropriate for the research model.

Unlike the SCLP, the maximal covering facility problem (MCLP) assumes that only a limited number of facilities can be placed, so not all demand nodes may be covered by the constrained number of facilities (Church and ReVelle, 1974:102). "The objective of the MCLP is to locate a predetermined number of facilities, *p*, in such a way as to maximize the demand that is covered" (Current et al, 2002:90). In this type of problem, the demand node is considered to be covered if it falls within a maximum distance of at least one chosen facility. In observing the constraints applicable to the missile maintenance scheduling problem, it was found the constraints placed on the number of facilities and maximum response time of the security umbrellas made the MCLP an ideal model for solving this problem.

In a p-center problem, often referred to as the minimax problem, "the maximal distance between each point [demand node] and its assigned facility is to be minimized by the best partition of the points [demand nodes] and the best location of facilities" (Drezner, 1986:312). The objective is to minimize the maximum distance between any demand node and its closest facility, given a predetermined number of facilities to be placed. An additional constraint is added which "requires that each demand node be assigned to exactly one facility" (Current et al, 2002:92). The p-center problem assumes that all demands are covered by the constrained number of facilities. This particular

facility location model could be applied to the missile maintenance scheduling program, but maximum response times would have to be ignored in order to cover all demands. As such, the p-center problem was not used during this research.

The p-dispersion problem (PDP) differs from the previous facility location models in two ways. The PDP is not concerned with distances between facilities and demand nodes, but the distances between the facilities themselves. "The objective is to maximize the minimum distance between any pair of facilities" (Current et al, 2002:93). Constraints for the maximum number of selected facilities and minimum distance between facilities are applied. This model assumes that all demand will be covered by the placed facilities. Again, this model is inappropriate for the missile maintenance scheduling problem because the maximum travel time between missile alert facilities is irrelevant; the important consideration is the travel time between the missile alert facilities and the scheduled launch facilities.

The p-median technique is a commonly used facility-location method for placing product distribution centers, retail outlets, and warehouses. The objective "consists of locating *p* facilities in a given space (e.g. Euclidean space) which satisfy *n* demand points in such a way that the total sum of distances between each demand point and its nearest facility is minimized" (Correa et al, 2001:1). The p-median method constrains the number of facilities that can be placed in a geographic area of interest. Weights can be applied to demand nodes that consider factors such as frequency of transactions, transportation costs, etc. The optimal facility location is found by minimizing the maximum weighted-average distance traveled from the demand point to each of the demand nodes. The p-median model also follows three basic assumptions:

> First, it assumes that each potential site has the same fixed costs for locating a facility at it. Secondly, it assumes that the facilities being sited do not have capacities on the demand that they can serve. In the parlance of the literature, it is an 'uncapacitated' problem. Finally, it also assumes that one knows, a priori, how many facilities should be opened. (Current et al, 2002:95)

As with the p-center facility location model, this technique could be applied to the missile maintenance scheduling program, but maximum response time constraints would have to be ignored in order to cover all demands.

Unlike the p-median problem, the fixed charge location problem (FCLP) does not assume equal facility costs, a fixed number of facilities, and unlimited facility capacity. By relaxing these assumptions, the FCLP seeks to discover the optimal number and location of facilities that minimize total transportation and facility costs. Demand nodes are not constrained to service by the closest facility, but the facility that best meets the needs of the demand node; however, the needs of each demand node can only be serviced by one facility (Current et al, 2002:95-96). As with the majority of the previous models mentioned, the FCLP does not allow for shortages; all demand nodes must be serviced by a facility. With alterations to the model components, the FCLP could be tailored to the missile maintenance scheduling problem. This would require the removal of facility and distance constraints, would require the consideration of transportation and facility costs (or manpower costs), and would require removal of the single-source demand constraint. Due to the model complexity and absence of required data, the FCLP was not considered a viable candidate for the research model.

The hub location model objective "minimizes the sum of the cost of moving items between a non-hub node and the hub to which the node is assigned, the cost of moving

from the final hub to the destination of the flow, and the interhub movement cost which is discounted by a factor of α" (Current et al, 2002:97). The objectives associated with the hub location model are beyond the scope of the missile maintenance scheduling problem, so were not considered in this research.

Finally, the maxisum location problem mathematical formulation is similar to that of the p-median problem, but takes an "obnoxious" approach to choosing facility location. This model "seeks the locations of *p* facilities such that the total demand-weighted distance between demand nodes and the facilities to which they are assigned is maximized" (Current et al, 2002:98). Such an objective is important when considering locations of facilities that could detrimentally impact a surrounding population center, such as nuclear power plants, landfills, and prisons. Due to nature of this facility location problem, it has no application to the missile maintenance scheduling problem researched in this thesis.

The missile maintenance scheduling problem seeks to accomplish the greatest amount of maintenance at launch facilities that fall within 2 security umbrellas, each with a maximum travel radius of 60 minutes. Of the eight facility location problems previously discussed, the MCLP is the model that most appropriately defines missile maintenance scheduling problem.

Evolution of the Maximal Covering Facility Problem (MCLP)

The MCLP was developed in 1974 by Richard Church and Charles ReVelle of Johns Hopkins University. This model evolved from the location set covering problem (LSCP) research performed in the early 1970's by Toregas and ReVelle (Church &

ReVelle, 1974:101). Unlike the LSCP, which covered all demand nodes within a maximum distance of a minimal number of facilities, Church and ReVelle's model considered that financial constraints could limit the number of facilities that would be placed. "Having realized that his resources (facilities) are insufficient to achieve total coverage within his distance goal, the decision maker may seek to cover as many [demands] as possible within *S* [maximal service distance] using those limited resources" (Church & ReVelle, 1974:102). In considering this resource limitation, the authors sought to develop a model that maximized the covered demand within the predetermined service distance by locating a set number of facilities. This model was named the Maximal Covering Location Problem (MCLP). Two solution techniques were used to solve the problem: heuristics and linear programming (LP).

The heuristic approach utilized the Greedy Adding (GA) and the Greedy Adding with Substitution (GAS) Algorithms. The GA Algorithm chose the location of the first facility that covered the most demand. The second facility was assigned a location that covered the most demand not covered by the first facility, and so on, until the maximum number of facilities was selected or all demand was covered. The GAS Algorithm was much like the GA Algorithm, but expanded upon the first heuristic by "trying to replace each facility one at a time with a facility at another 'free' site" at each iteration (Church & ReVelle, 1974:106). Facility locations that provided an improvement over the previously placed facility were substituted into the solution set. The authors noted that though these heuristic algorithms calculated maximum coverage for each facility, globally optimal answers were not guaranteed. However, the LP method was also used to find optimal problem solutions. Two cases of the solution set were observed; the first

case produced “all-integer answers” for the decision variables, while the second case produced “fractional answers.” When the solution set terminated with “all-integer answers,” which occurred nearly 80 percent of the time, the optimal solution was determined. Solutions with “fractional answers” had to be resolved using a method of inspection or Branch and Bound techniques. (Church & ReVelle, 1974:107-109).

A comparison of the 2 solution methods showed that the heuristic algorithms produced nonoptimal solutions approximately 55 percent of the time, but demand node coverage was no lower than 90 percent of the optimal answer. The average computation time for the LP method was 11.02 seconds, while the average heuristic computation time was 14.24 seconds. As such, the LP method was found to produce superior answers in a shorter calculation time than the heuristics. The authors concluded that the “enlightened use of the maximal covering location problem appears to lead to superior patterns of population coverage” (Church & ReVelle, 1974:118).

Since the development of the first MCLP, many variations of the original model have been constructed. The following examples of expanded MCLP models are by no means all inclusive, as numerous studies that have been performed on location analysis.

In 1979, Church and Meadows “generalized the search for on optimal solution to a dominant set of points NIPS (Network Interest Point Set) which includes in addition to the nodes also all points that are T units of distance away from any demand point” (Berman, 1994:432). As with the original MCLP model, linear programming and branch and bound methods were used to achieve optimal solutions.

A two-level hierarchical covering location problem (HCLP) was developed in 1982 by Moore and ReVelle. This particular problem looked at locating facilities that

provided different levels of service to the demand nodes. Specifically, the article applied the two-level hierarchical model to health care services in Honduras. The lower-level facilities (clinics) provide only a level one service, while the higher-level facilities (hospitals) provide both level one and level two services (Moore and ReVelle, 1982). Espejo et al (2003) expanded on the HCLP model, developing solutions using dual-based heuristics; specifically, a sub gradient-based heuristic incorporating a Lagrangean-surrogate relaxation, which reduced to a 0-1 knapsack problem. The researchers discovered that the dual-based heuristic produced satisfactory results in a fraction of the time required to produce an optimal solution using CPLEX.

In the article, *The Maximum Coverage Location Problem*, Megiddo et al (1983) considered locating new facilities within a pre-existing network of established facilities, with the goal of "drawing" a maximum number of customers. "There is thus some competitive flavor to such problems in that the existing facilities may belong to one company while a second company is trying to extract the maximum profit by locating its own facilities on the same network" (Megiddo et al, 1983:253). In this article, an algorithm was developed to solve such problems using a tree network.

In addition, Berman (1994) studied the relationship between p-maximal cover problems and partial center problems on networks. This study paved the way for the creation of the generalized maximal covering location problem (GMCLP), developed by Berman and Krass in 2002. Unlike the original MCLP, this model did not consider demand coverage as binary, where demand nodes that fell within the maximum distance of the facility were considered fully covered (assigned a value of one), while demand nodes that fell outside of this maximum were considered uncovered (assigned a value of

zero). Instead, the GMCLP assumed “that the coverage level is a decreasing step function of the distance to the closest facility…” (Berman & Krass, 2002: 564). This problem was solved using greedy heuristics and integer programming.

In the article, *The Maximal Conditional Covering Problem*, ReVelle et al (1996) considered an extension of the MCLP that not only required demand nodes within a certain distance to be covered by a facility, but also required that the facilities themselves be covered by other facilities within a different coverage radius. This redundancy of demand and facility coverage was applied to emergency services, where more than one facility may be required to cover overall network demand. (ReVelle et al, 1996).

One study was found that closely parallels the specific research of this thesis. In his research, Ma (2003) integrated scheduling and MCLP methodologies to determine police patrol areas for the Dallas Police Department. The objective of the Police Patrol Area Covering problem (PPAC) was to “maximize the number of incidents served or ‘covered’ within the desired response time” (Ma, 2003:8). Demand nodes were areas where incidents were expected to happen, while facilities were considered the police cars on patrol. A combination of the Geographic Information Systems (GIS) and the Optimization Programming Language (OPL) linear programming solver software was used to develop solutions. Ma concluded that PPAC technique provided optimal solutions for assigning police patrol areas to meet the objective function and would improve the level of service over previous methods used.

Problem Solving Techniques

A variety of techniques can be employed to solve the MCLP. Two common methods used are optimization and heuristics. Optimization, also known as mathematical programming, is defined as "a field of management science that finds the optimal, or most efficient, way of using limited resources to achieve the objectives of an individual or business" (Ragsdale, 2004:17). Heuristics are a "rule-of-thumb" method for generating feasible, but not necessarily optimal, solutions. Table 2 provides the advantages and disadvantages of each technique.

Table 2. Optimization versus Heuristics (Eberlan, 2004:49)

	Advantages	**Disadvantages**
Optimization	1. Guaranteed best possible solution given assumptions and data. 2. Can accurately handle all forms of costs (variable and fixed). 3. Creative solutions not considered before can be uncovered. 4. Permits more efficient analysis of problems (economizes data efforts). Often results in significant cost savings.	1. Can assume away the problem. 2. Optimization cannot be used for full range of logistic problems. 3. "Black box" syndrome (some managers do not understand mathematical algorithms behind technique). 4. Optimal solutions do not prescribe operating rules for implementation. 5. Tough to use in larger models.
Heuristics	1. Allow optimal or near optimal solutions. 2. Solution time is reduced. 3. Solution satisfying (close solution good enough). 3. Best to use when resources are constrained. 4. Heuristics can do a better job of accurately describing the problem.	1. Solution is not optimal 2. Do not handle capacities and fixed costs well.

The technique used to solve the location problem is highly dependent on several factors, which are specific to the individual problem. The type of objective function, decision variables, and constraints, problem complexity, needs of the end user, and computational

time required to solve the problem are all factors that must be considered when developing a tool to produce problem solutions.

Classification of Optimization Models

Optimization models can be classified in several ways. Table 3 below identifies the different types of optimization models and characteristics of each model.

Table 3. Characteristics of Optimization Models (Rardin, 1998)

Model Classification	Characteristics
Linear Program (LP)	1. Single objective function and all constraint functions are linear in the decision variables. 2. Weighted factors take on a constant value. 3. Variables are in the first power. 4. Decision variables take on positive, continuous values. 5. Involves constant-weighted sums of decision variables. 6. Each unit change in a decision variable has the same effect as the preceding change.
Nonlinear Program (NLP)	1. Single objective function or any constraint function is nonlinear in decision variables. 2. Involves negative powers of decision variables. 3. Involves products and quotients, powers not 1, and logarithms of decision variables. 4. Weighted factors take on changing values. 5. Decision variables take on positive or negative, continuous values.
Integer LP (ILP) Integer NLP (INLP) or Discrete Optimization Models	1. Takes on characteristics of one of previous two models, but at least one decision variable is limited to a fixed or countable set of values (whole or binary numbers only) 2. If all decision variable values are discrete, then model is a pure integer program. 3. If at least one, but not all, decision variable values are discrete, then model is a mixed-integer program.
Multiobjective Optimization Model	1. Takes on characteristics of any one of the previous models, but maximizes or minimizes two or more objective functions simultaneously. 2. No single criterion appropriately or fully captures the objective of the problem. 3. Conflicts among objectives usually make this model less tractable than single objective models. 4. It is not clear how to define an "optimal" solution.

According to the literature, "the maximal covering problem is NP-hard (Megiddo, Zemel, and Hakimi, 1983), but it can generally be solved effectively using heuristics" (Current et

al, 2002:90). Non-deterministic Polynomial hard (NP-hard) refers to the computational complexity of the problem. As the size and complexity of the problem increases, the ability to optimally solve the problem within a reasonable period of time, or polynomial time, becomes impractical. Generally, heuristics can be developed and used to solve problems of this nature.

Heuristics

Ragsdale (2004) defines a heuristic as "a rule-of-thumb for making decisions that might work well in some instances, but is not guaranteed to produce optimal solutions or decisions" (Ragsdale, 2004:79). Heuristics are used when the size of a particular problem is beyond the computational limits of available optimization algorithms, given a restricted amount of calculation time. Managers often choose to use heuristics when they cannot justify the cost, time, and/or resources needed to find an optimal answer. Heuristics provide managers with "good" solutions, or feasible solutions that are close to optimal. Occasionally, the optimal solution is achieved using the heuristic method.

Research Model Selection

Previous military and civilian research has analyzed problems related to this research, but none were found that specifically addressed the entire realm of maintenance scheduling within ICBM organizations. After a review of the literature and analysis of problem-solving techniques available, the missile maintenance scheduling problem exhibited characteristics that would be best analyzed by the MCLP model. Ideally, optimization would be used to produce daily schedules of launch facilities requiring open

holes or site penetration. However, the existence of multiple objectives, the large problem size, and software limitations made pure optimization infeasible. The resulting two-stage heuristic model uses discrete optimization within each stage to produce feasible solutions to the missile maintenance scheduling problem.

Summary

This chapter defined several key terms being used throughout this thesis. DoD and Air Force directives relevant to this research were discussed. Previous ICBM maintenance and security forces scheduling initiatives were described, as well as the scheduling procedures currently used by missile maintenance schedulers at F. E. Warren AFB, WY. A history of location analysis, the maximal covering location problem methodology, and its application to this thesis were also provided. Finally, characteristics of optimization models and heuristics were discussed. Chapter III describes the methodologies employed to solve the problem studied in this research.

III. Methodology

Introduction

This chapter fully describes the problem, model, the type of data collected, and how it was analyzed. It also introduces the methods used to form the basis of the analysis. The location analysis method utilized and solution techniques employed are described, and the mathematical formulation of the research model is provided. The methods employed to verify the Microsoft Excel® Premium Solver™ solutions and to select the appropriate solution technique are presented. The resulting solutions to the constructed model form the basis of the results analysis performed in Chapter IV.

Problem/Purpose Statement

Security waivers are currently in place which enable ICBM managers to offset the initial shock of increased security requirements dictated by DoD and Air Force instructions. However, waivers only serve as a temporary solution to the looming, more permanent changes to maintenance scheduling practices that must occur to properly sustain our land-based nuclear deterrent force. Missile maintenance managers must employ enhanced maintenance scheduling techniques that can compensate for the limited number of security personnel available, while attempting to maintain adequate levels of weapons system integrity.

Theoretical Model

The hypothesis is that maintenance scheduling activities at F. E. Warren AFB missile launch facilities can be improved using the maximal covering facility problem

(MCLP) methodology to ensure that the weighted sum of scheduled launch facilities is maximized. This two-stage model first selects 2 security umbrella staging areas, of the 15 possible locations, that maximize the weighted sum of all launch facility maintenance activities eligible to be scheduled. Candidate launch facilities must meet the following criteria: fall within the established 60-minute response time; need maintenance accomplished that requires the presence of security personnel; the appropriate type and quantity of maintenance teams for specific maintenance tasks are available; and the appropriate type and quantity of security personnel are available. The second stage of the model seeks to determine a maintenance schedule comprised of launch facilities that are covered by the security umbrellas determined by the first stage, given maintenance team and security manpower constraints. Current missile maintenance scheduling methods are discussed in Chapter II of this thesis. The research model solutions are compared to the weighted sum of actual maintenance activities accomplished during May 1-26, 2005.

Data

The data for this thesis was collected from the 90th Space Wing at F. E. Warren AFB, WY:

- Daily Status Sheets from May 1-26, 2005
- Daily security escort availability and number requested by maintenance
- Daily pre-schedules developed by Scheduling section, May 3-30, 2005
- Alert Status Sheets from May 1-31, 2005
- Activation/Deviation worksheets from May 1-31, 2005
- IMMP Work Order Completion spreadsheet, January to June 2005

- Matrix of distances from MAFs to LFs (Dawson, 2005)

All data reflects historical records maintained at F. E. Warren AFB and was obtained from the 90th Maintenance Operations Squadron and 790th Missile Security Forces Squadron. Dawson (2005) provides the specific mathematical formulations used to create the geographical distance matrix, which was also used in this research.

Data Aggregation

Three data sets, including the daily pre-schedules, daily status sheets, and the IMMP work order completion spreadsheets, all provided a wealth of information that when combined, formed a complete picture of total maintenance activities accomplished each day. Specific information included: the type of maintenance activities available, scheduled, and performed; location of maintenance activities; quantity and type of maintenance teams available; quantity and type of maintenance teams required to complete specific maintenance tasks; priority designator of specific maintenance tasks, and quantity of security escort teams (SETS)/other security guards required and available. By combining information from the 3 data sets, a complete baseline schedule was constructed for each of the 26 days. The final daily schedules served as the historical inputs, which were then compared to the daily schedules created by this model.

Some data is subject to interpretation because the daily pre-schedules, daily status sheets, and work order completion spreadsheet were accomplished at different stages of the scheduling process. Maintenance cancellations and deviations occur on a regular basis, resulting in schedules that appear to conflict. The most common inconsistencies

observed were the quantity of SETS required versus available, scheduled versus completed maintenance activities, and number of SETS required to perform specific maintenance activities. To account for these inconsistencies, the total quantity of SETS required and available was taken directly from the daily status sheets from F. E. Warren AFB, as it is the most accurate historical scheduling record. If a maintenance activity was shown as completed in the work order completion spreadsheet, but was not listed on the daily pre-schedule or daily status sheet, that maintenance activity was added to the final schedule. The daily pre-schedules were the final authority on number of SETS required for each maintenance activity, as well as the number and types of maintenance teams available for duty. In the end, a final aggregate historical schedule was achieved.

Modeling Approach

Based on the examination of facility location methods in Chapter II, the MCLP methodology was used as the basis for the model. Microsoft Excel® with the Premium Solver™ plug-in was chosen as the optimization software to create the model, due to the availability and user-friendly nature of the software. The advantages and disadvantages for optimization and heuristics provided in Chapter II were considered. Heuristics are best to use when resources are constrained and allow for optimal, or near optimal, solutions with a reduced processing time. Over the course of developing a research model, it was found that a two-stage heuristic, each stage utilizing optimization techniques, was the most reasonable approach to produce the final model solutions for this multiple objective problem.

Critical Model Parameters

The critical model parameters are those essential elements required to produce a model that accurately depicts the process under analysis. The elements deemed necessary for this research include:

1. Type and quantity of missile maintenance teams available.

2. Quantity of SETS and other security personnel available.

3. Number of supportable security umbrellas.

4. Maximum security response time from umbrella focal points (MAF) to demand points (LF).

5. Complete list of maintenance actions at LFs that are capable of being performed, given available maintenance teams and security personnel.

6. Approximate travel times from each MAF to every LF.

In order for a launch facility to be selected as part of the final solution set, it must fall within at least one of the supportable security umbrellas, must require the presence of security forces personnel for maintenance task completion, and must have the appropriate type and quantity of missile maintenance teams and security personnel available. Launch facilities requiring maintenance that do not meet these criteria are eliminated from the candidate set, as they introduce bias into the stage-one, security umbrella location solution. Maintenance actions that do not require security forces presence are exempt from the umbrella concept, as they are not constrained to predefined locations within the missile complex.

Model Objective

Specific guidance from AFSPCI 21-114, *Intercontinental Ballistic Missile (ICBM) Maintenance Management*, was used to develop the objective function of the research model. Paragraph 1.1, “ICBM Maintenance Management,” states that

> All maintenance actions and management efforts must be directed towards **maximum availability of ICBMs** in support of the United States Strategic Command(USSTRATCOM) requirements directives. All maintenance supervisors are mandated to use all resources in the most effective and efficient way with emphasis on the safety and welfare of the technician… (AFSPCI 21-114, 2003)

To successfully fulfill this objective, maintenance efforts must focus on completing those maintenance activities that are crucial to keeping a maximum number of ICBMs on full alert status, given manpower, equipment, and environmental constraints. AFSPCI 21-114 provides further direction for which maintenance activities are most crucial to sustaining the “maximum availability of ICBMs.” Attachment 2, “Missile Maintenance Priority Designators,” provides a detailed breakdown of maintenance activity prioritization and can be viewed in Appendix A. It utilizes a priority scale of one through nine, with one representing the most critical maintenance tasks and nine representing “deferred discrepancies.”

To quantify how effective the maintenance schedulers were at meeting the published objective, a weighting factor was applied to each type of maintenance activity. Due to the large variety of maintenance tasks that are performed, all tasks were grouped into 18 separate categories to create the weighting for this research. Categories were based on priority designation, extent of coordination efforts required, mission impact,

level of security presence required, and practicality of completion. The category breakdown and rationale for ranking are listed in Appendix B.

Weights were assigned to each category based on an exponential distribution of the 18 categories. An exponential distribution was chosen because of its ability to assign a greater weight and higher degree of separation to the maintenance tasks most critical to maximizing the quantity of ICBMs on alert, while gradually leveling the impact of the weights as the probability distribution frequency (PDF) curve approaches the least critical categories. Various values for λ, which determine the shape of the PDF curve, were tested in order to assign category weights. A λ value of 0.25 produced category weights that provided a sufficient level of separation between high and low-priority categories, without making the weights of the last several categories equal. The four periodic maintenance activities were broken out into separate categories due to different security and maintenance team requirements. However, all four categories were given a weight of 21, as all are equal in priority and mission importance. Later model experimentation demonstrated that in several cases, the weighted sum of several low-priority categories would exceed the weight of a higher-priority category. Because the top three maintenance category weights have the greatest impact on achieving the published objective, their weights were multiplied by a factor of three in order to provide a sufficient level of separation to avoid repeat results. Continued pilot-testing proved this adjustment was effective. The final categories and weights utilized by the research model are shown in Figure 1.

Weighted Priorities	
MXS Event	Weight
LLC/RS	585
PML Off-Alert	456
Off-Alert	357
Priority 1	92
Concrete Headworks	72
PRP	56
NMC MAF	44
LF Security C/O	34
TS Priority 3	27
CCT	21
PMT	21
RVM	21
PRP Open Hole	21
Priority 2-3	16
Batteries	13
Training	10
Priority 4-7	6
Misc. MAF	4

Figure 1. Maintenance Categories and Weights

After the final weights were applied to the maintenance activities in the 18 maintenance categories, a total weighted value of the maintenance required for each candidate launch facility was computed. To fulfill the published objective and measure overall scheduling effectiveness, the research model aims to maximize this weighted sum of maintenance activities at all launch facilities that meet the criteria previously outlined in this chapter.

Model Decision Variables

The research model has two different sets of decision variables. In stage 1, the 15 missile alert facilities serve as the decision variables, which are binary in nature; selected missile alert facilities are given a value of 1, while all others are assigned a value of 0. Given all launch facilities assigned to the candidate set, the model selects two missile alert facilities that cover the maximized weighted sum of maintenance at all candidate

launch facilities. The two selected missile alert facilities establish the umbrella focal points required in stage two.

The decision variables for stage 2 are the 150 Minuteman III launch facilities, which are also binary in nature. Given the stage one solution set, the model maximizes the weighted sum of a selected subset of launch facilities that fall within 60-minutes of the two selected security umbrella locations, given maintenance and security personnel constraints. In other words, a sub-set of launch facilities covered by the stage one security umbrellas are picked to be on the daily schedule. The stage-two solution provides a list of launch facilities covered by the security umbrellas and with the highest weighted total. The maintenance teams and security personnel not utilized in the final model solution can then be assigned to maintenance activities exempt from security umbrellas, or removed from the daily schedule completely.

Model Constraints

Stage one requires the following three constraints: decision variables are binary; the solution set must include at least one, but no more than two missile alert facilities; and all launch facilities considered by the objective function must fall within at least one of the 60-minute security umbrellas provided in the solution set. In stage two, the following constraints further limit the field of solutions:

- # of SETS used ≤ # of SETS available
- # of Other Guards used ≤ # of Other Guards available
- # of Battery (BATT) teams used ≤ # of BATT teams available
- # of Corrosion Control Teams (CCT) used ≤ # of CCT available

- # of Civil Engineering (CE) teams used $\leq$ # of CE teams available
- # of Electro-Mechanical Teams (EMT) used $\leq$ # of EMT available
- # of Facility Maintenance Teams (FMT) used $\leq$ # of FMT available
- # of Missile Handling Teams (MHT) used $\leq$ # of MHT available
- # of Missile Maintenance Teams (MMT) used $\leq$ # of MMT available
- # of Periodic Maintenance Teams (PMT) used $\leq$ # of PMT available
- # of Pneudraulics (PNEU) teams used $\leq$ # of PNEU teams available
- # of Rivet Mile (RVM) teams used $\leq$ # of RVM teams available
- # of Training (TRN) teams used $\leq$ # of TRN teams available
- Decision variables are binary
- The final launch facility solution set must fall within the 60-minute security umbrellas established in the stage-one solution set

Mathematical Formulation

"The maximal covering location problem (MCLP) addresses the issue of locating a predefined number of facilities in order to maximize the number of demand points that can be covered. (Karasakal and Karasakal, 2004:1515). This research objective differs slightly from the above definition by maximizing the weighted demand of launch facilities that can be covered by a predefined number of missile alert facilities. Based on previous discussion of objectives, decision variables, and constraints, the notations used to define the variables in stage one are as follows:

L = the set containing 150 launch facilities (A02, A03, …, O11);

M = the set containing 15 missile alert facilities (A01, B01, …, O01);

P = maximum number of missile alert facilities (security umbrella centers);

R = maximum security umbrella response time;

i = the index of candidate missile alert facilities;

j = the index of candidate launch facilities;

w_j = weight of maintenance activity at launch facility j;

x_j = binary condition indicating whether or not launch facility j is covered;

a_{ij} = binary condition indicating whether or not the response time between missile alert facility i and launch facility j falls within the maximum specified response time;

r_{ij} = the response time between missile alert facility i and launch facility j;

Y_i = binary condition indicating whether or not missile alert facility i is selected as the security umbrella center;

The MCLP mathematical formulation for stage one is as follows (Church and ReVelle, 1974):

$$\text{MAXIMIZE} \quad \sum_{j=1}^{L} w_j x_j \tag{1}$$

$$\text{SUBJECT TO:} \quad \sum_{i \in M} a_{ij} Y_i \geq x_j \qquad j = 1,..,L \tag{2}$$

$$\sum Y_i \leq P \tag{3}$$

$$Y_i = \{0, 1\} \quad \forall i \tag{4}$$

$$\text{WHERE:} \quad a_{ij} = \begin{cases} 1 \text{ if } r_{ij} \leq R \\ 0 \text{ otherwise} \end{cases}; \quad \forall\, i \text{ and } j \tag{5}$$

$$x_j = \begin{cases} 1 \text{ if } \sum_{i \in M} a_{ij} Y_i \geq 1 \\ 0 \text{ otherwise} \end{cases}; \quad j = 1,\ldots L \tag{6}$$

$$Y_i = \begin{cases} 1 \text{ if missile alert facility } i \text{ is selected} \\ 0 \text{ otherwise} \end{cases}; \quad (7)$$

$$j \in L, \; i \in M \quad (8)$$

The objective function (1) maximizes the sum of weighted demands at covered launch facilities. Constraint (2) ensures that launch facility *j* is not considered unless it falls within the maximum response time of at least one selected missile alert facility, *i*. Constraint (3) states that no more than *P* missile alert facilities can be selected as a security umbrella center. Constraint (4) is the binary constraint placed on the decision variables. Condition (5) assigns a_{ij} a value of 1 if the response time between missile alert facility *i* and launch facility *j* is less than, or equal to, the maximum allowable response time, *R*; a value of 0 is assigned if the maximum response time is exceeded. Condition (6) assigns x_j a value of 1 if launch facility *j* is covered by at least one selected missile alert facility, *i*, which is a member of the set of all missile alert facilities, *M*; a value of 0 is assigned if launch facility *i* is not covered. Condition (7) assigns Y_i a value of 1 if missile alert facility *i* is chosen as the security umbrella center; otherwise, it takes on the value 0. Condition (8) states launch facilities, *j*, are members of the set of all launch facilities, *L*; likewise, missile alert facilities, *i*, are members of the set of all missile alert facilities, *M*.

Stage two utilizes the solutions from stage one to compute the final model solution. The notations used to define the variables in stage two are as follows:

X = the solution set of launch facilities covered by the missile alert facilities selected in stage one;

Y = the solution set of missile alert facilities selected in stage one of the model;

i = the index of selected missile alert facilities;

j = the index of candidate launch facilities;

t = the index of maintenance/security team types (SETS,…, TRN);

w_j = weight of maintenance activity at launch facility j;

x_j = binary condition indicating whether or not launch facility j is selected;

a_{ij} = binary condition indicating whether or not the response time between missile alert facility i and launch facility j falls within the maximum specified response time;

c_{jt} = number of teams of type t required at launch facility j;

C_t = total number of available maintenance/security teams, t;

The MCLP mathematical formulation for stage two is as follows (Church and ReVelle, 1974):

$$\text{MAXIMIZE} \quad \sum_{j=1}^{X} w_j x_j \tag{1}$$

$$\text{SUBJECT TO:} \quad \sum_{i \in Y} a_{ij} \geq x_j \qquad j = 1,\ldots,X \tag{2}$$

$$\sum_{j=1}^{X} c_{jt} \leq C_t \qquad t = \text{SETS},\ldots,\text{TRN} \tag{3}$$

$$x_j = \{0, 1\} \ \ \forall\, j \tag{4}$$

$$\text{WHERE:} \quad x_j = \begin{cases} 1 \text{ if launch facility } j \text{ is selected} \\ 0 \text{ otherwise} \end{cases}; \tag{5}$$

$$j \in X\ ,\ i \in Y \tag{6}$$

The objective function (1) maximizes the sum of weighted demands at covered launch facilities. Constraint (2) ensures that launch facility j is not selected unless it falls within the maximum response time of at least one of the two selected missile alert facilities, i.

Constraint (3) states that the sum of maintenance and security teams t required at all selected launch facilities must be less than, or equal to, the total number of each maintenance and security team available, C_t. Constraint (4) is the binary constraint placed on the decision variables. Condition (5) assigns x_j a value of 1 if launch facility j is chosen for the schedule; otherwise, it takes on the value 0. Condition (6) states that launch facilities j are members of the solution set of launch facilities covered by the missile alert facilities selected in stage one, X; likewise, missile alert facilities i are members of the solution set from stage one, Y.

Analysis of Microsoft Excel® Premium Solver™ Algorithms

Once the mathematical formulations were devised and the research model constructed, several tests were run to find which Premium Solver™ algorithms produced the most reliable solutions within a reasonable period of time. Premium Solver™ provides model designers with three different types of algorithms to produce solutions to mathematical models. For linear programming, the Standard Simplex LP method is used. This algorithm "assumes that the objective function and constraints are linear functions of the variables" (Fylstra et al, 1998:1). This method is extremely accurate, fast, and produces a globally optimal solution in nearly every situation. The Standard Generalized Reduced Gradient (GRG) Nonlinear method "assumes that the objective function and constraints are smooth nonlinear functions of the variables" (Fylstra et al, 1998:2). It is accurate, fast, and yields a locally optimal solution, but does not necessarily provide a globally optimal solution. To converge on the globally optimal solution, the adjustable model cells, which represent the decision variables, can be given initial values that are

"widely separated" and the various solutions compared to discover the best solution. The final Premium Solver™ method available to model designers is the Standard Evolutionary method. Four local search patterns exist within this method: Randomized Local, Deterministic Pattern, Nonlinear Gradient, and Linear Local Gradient. Each local search pattern uses a different method of manipulating the model's decision variable values to converge on a locally optimal solution. The evolutionary algorithm "makes almost no assumptions about the relationships between the decision variables, and the objective function and constraints" (Fylstra et al, 1998:2). This algorithm is much slower than the first two algorithms, often produces good, sub optimal solutions, and run time or iteration limits must be established to keep the model from running indefinitely.

Model Validation and Verification

Five years of missile maintenance officer experience provided a level of knowledge sufficient to build validity into the model. During the developmental stages, weighting factors, maintenance categories, and the model stages themselves were adjusted until the model was able to produce solutions that were realistic and comparable to an actual maintenance schedule. Several experienced missile maintenance officers and senior noncommissioned officers from F. E. Warren AFB, WY, and Maxwell AFB, AL, further validated the model results during their thesis reviews and edits.

Based on the information concerning the three Premium Solver™ methods discussed previously, attempts were made to solve the two-staged research model using all available Premium Solver™ algorithms. In stage one of the model, the first constraint shows an interaction between the Y_i and x_j decision variables that distinguishes it as a

nonlinear model. These nonlinear characteristics eliminated the Standard Simplex and Standard Evolutionary, Linear Local Gradient techniques from the pool of applicable test algorithms for that stage. The remaining 4 algorithms were used to provide stage 1 solutions for all 26 daily schedules. In stage two of the model, the constraint that characterized stage one as a nonlinear model is removed. All remaining constraints are linear in nature, making stage two a linear model. As such, the Standard Simplex LP was used to solve the second stage.

Test for Model Consistency.

To address the problem of local versus global optimality, the initial values for the decision variables in each stage were toggled between all zeros and ones prior to solving. Doing this set the decision variable initial values to each extreme of the solution region, so that the solutions from each region could be compared for consistency. Four different combinations of toggled decision variable values were tested on each of the 4 algorithms for all 26 daily schedules. The final test results can be observed in Appendix C. The results indicate that toggling the decision variable initial values between zero and one in stage one occasionally produced different final solutions in all three of the Standard Evolutionary algorithms, but had no effect on solutions when using the Standard GRG Nonlinear method. Toggling the initial values of the stage two decision variables had no impact on the final model solutions. This fact was considered during final model analysis. Table 4 summarizes the results of the model consistency verification.

Table 4. Consistency of Excel Solver Algorithms

	Standard Evolutionary Search Algorithms									Standard GRG Nonlinear			Actual Schedule	
Date	Random Localized			Deterministic			Nonlinear Gradient							
Settings	Total Weight	Sites	Consistent ?	Total Weight	Sites	Consistent ?	Total Weight	Sites	Consistent ?	Total Weight	Sites	Consistent ?	Total Weight	Sites
1-May-05	302	9	Yes	302	9	Yes	302	9	Yes	302	9	Yes	286	8
2-May-05	475	10	Yes	475	10	Yes	475	10	Yes	465	10	Yes	459	9
3-May-05	555	10	Yes	555	10	Yes	555	10	Yes	555	10	Yes	464	8
4-May-05	407	12	Yes	407	12	Yes	407	12	Yes	407	12	Yes	334	10
5-May-05	404	12	Yes	383	11	Yes	404	12	Yes	383	11	Yes	340	9
6-May-05	280	5	Yes	280	5	Yes	280	5	Yes	280	5	Yes	275	5
7-May-05	75	4	Yes	75	4	Yes	75	4	Yes	75	4	Yes	75	4
8-May-05	27/16	1	No	27	1	Yes	27	1	Yes	27	1	Yes	27	1
9-May-05	604	9	Yes	604	9	Yes	604	9	Yes	604	9	Yes	577	8
10-May-05	261	4	Yes	261	4	Yes	261	4	Yes	261	4	Yes	240	4
11-May-05	253/264	6	No	253	6	Yes	264/253	6	No	264	6	Yes	242	5
12-May-05	274	6	Yes	269/263	6	No	274/269	6	No	269	6	Yes	248	5
13-May-05	99	3	Yes	89/99	3	No	99	3	Yes	99	3	Yes	88	3
14-May-05	59/48	3	No	59/48	3	No	59	3	Yes	59	3	Yes	32	2
15-May-05	71/82	3	No	82/71	3	No	82	3	Yes	82	3	Yes	66	3
16-May-05	547/531	10/9	No	531/544	9/10	No	547	10	Yes	547	10	Yes	520	9
17-May-05	288	5	Yes	288	5	Yes	288	5	Yes	288	5	Yes	221	4
18-May-05	308	5	Yes	308	5	Yes	308	5	Yes	308	5	Yes	308	5
19-May-05	646	5	Yes	646	5	Yes	646	5	Yes	646	5	Yes	646	5
20-May-05	220	7	Yes	220	7	Yes	220	7	Yes	220	7	Yes	158	4
21-May-05	131	5	Yes	131	5	Yes	131	5	Yes	131	5	Yes	131	5
22-May-05	238	8	Yes	238	8	Yes	217/238	7/8	No	238	8	Yes	216	8
23-May-05	545	8	Yes	534/545	8	No	534/540	8	No	545	8	Yes	545	8
24-May-05	165	7	Yes	165/154	7	No	165/154	7	No	165	7	Yes	137	7
25-May-05	257/247	7/6	No	257/247	7/6	No	247/220	6/5	No	257	7	Yes	225	6
26-May-05	321	4	Yes	321	4	Yes	321	4	Yes	321	4	Yes	321	4
Total			20			18			20			26		
%			76.92			69.23			76.92			100.00		

The Deterministic Pattern local search produced consistent results in approximately 69 percent of the daily schedules. The Random Localized and Nonlinear Gradient local search patterns both produced consistent results for approximately 77 percent of the daily schedules. All three Standard Evolutionary methods had one instance where final solutions were less than the actual maintenance schedule solution. Standard GRG Nonlinear was the only method to produce 100 percent consistent results. Additionally, it was the only method to produce solutions that were as good as, or better than, the actual maintenance schedule solutions for all 26 daily schedules. However, in three instances, the Standard GRG Nonlinear method produced results that were sub optimal, as compared to the three Standard Evolutionary methods. The sub optimality issue is addressed later on in this chapter. Based strictly upon the results of the consistency test,

the Standard GRG Nonlinear method appeared to be the technique of choice for producing stage one solutions in future revisions of the research model.

Calculation of Solution Times.

A summary of stage one calculation times can be seen in Table 5 below.

Table 5. Calculation Time for Selected Excel Solver Algorithms

	Standard Evolutionary Search Algorithms Calculation Time (seconds)						Standard GRG Nonlinear		Standard GRG Nonlinear (3)	
Date	Random Localized		Deterministic		Nonlinear Gradient					
Settings	0	1	0	1	0	1	0	1	0	1
1-May-05	94.07	84.46	64.65	102.09	64.43	93.89	5.15	5.4	11.31	11.5
2-May-05	80.28	90.37	115.93	107.95	123.89	84.72	5.67	5.68	6.2	6.39
3-May-05	64.93	112.93	119.45	82.7	119.31	118.46	5.41	5.78	7.01	7.15
4-May-05	119.84	85.37	75.67	64.67	88.39	138.23	5.67	5.82	7.23	7.36
5-May-05	98.06	97.84	75.1	106.53	143.59	140.82	4.06	4.36	4.76	4.98
6-May-05	87.53	65.58	87.34	83.87	96.95	85.87	4.02	4.72	4.53	4.59
7-May-05	87.72	77.59	87.67	109.32	88.78	78.09	4.35	4.59	4.32	4.64
8-May-05	101.96	82.15	112.2	84.32	93.92	88.26	4.45	4.54	4.32	4.58
9-May-05	81.51	90.24	84.76	88.21	102.67	64.48	3.67	3.84	4.39	4.46
10-May-05	81.87	65.56	110.45	83.93	84.96	98.67	4.29	4.32	4.87	5.04
11-May-05	127.04	97.72	121.68	79.34	81.23	86.61	4.76	5.2	4.73	4.86
12-May-05	80.39	89.65	120.45	111.49	96.36	172.06	4.21	4.15	4.58	4.7
13-May-05	90.43	75.96	74.8	64.24	119.37	75.15	3.68	3.92	4.43	4.67
14-May-05	65.53	67.17	113.56	85.8	122.28	94.02	4.28	4.46	5	5.18
15-May-05	75.96	128.14	64.5	87.7	94.36	91.78	4.37	4.45	5	5.14
16-May-05	145.19	71.34	64.45	146.89	100.84	129.2	6.76	6.87	6.5	6.73
17-May-05	152.21	78.42	78.28	107.18	94.72	82.67	4.31	4.78	4.95	5.09
18-May-05	112.58	66.1	103.61	85.17	84.12	160.14	4.1	4.2	4.67	4.81
19-May-05	73.62	75.64	107.18	104.78	100.06	103.01	4.45	4.64	5	5.15
20-May-05	74.89	88.2	121.87	64.46	96.73	76.92	4.65	4.81	4.42	4.62
21-May-05	96.5	103.04	87.95	79.27	91.18	126.62	4.68	5.1	4.65	4.93
22-May-05	77.15	117.24	97.26	95.62	85.89	125.86	5.01	5.06	4.43	4.68
23-May-05	104.36	123.29	79.4	81.48	24.58	128.31	6.04	6.15	5.93	6.12
24-May-05	73.67	82.56	60	127.23	189.61	132.12	4.32	4.51	4.29	4.48
25-May-05	88.29	81.75	85.17	31.24	93.64	88.75	4.34	4.5	5.75	5.87
26-May-05	100.37	107.92	88.89	59.04	93.72	80.37	4.21	4.34	4.82	5.02
Average	93.69	88.70	92.40	89.40	99.06	105.58	4.65	4.85	5.31	5.49

Total solution time can be an important consideration when selecting an optimization technique. As such, solution times for all stage one outputs were recorded during the consistency tests. The stage 2 solution times were not recorded because they were constantly less than 10 seconds for all 4 algorithms tested. Observe the average solution time calculated for each model in Table 5. It is evident that the Standard GRG Nonlinear technique outperforms the 3 Standard Evolutionary techniques, producing solutions anywhere from 17 to 20 times faster than the other methods. The last two columns of Standard GRG Nonlinear solution times were recorded after model convergence tolerances were tightened. This is discussed further in the next section. The tolerance

changes had very little impact on average solution time, as the average time increased by less than one second. The results from the solution time analysis also indicate that the Standard GRG Nonlinear method is the best technique to use for stage one of the research model. One final test was performed on the research model to test the repeatability of solutions using the Standard GRG Nonlinear algorithms.

Test for Model Repeatability.

To test for repeatability of model solutions, each of the 26 daily schedules was solved 2 additional times. All stage one and stage two decision variable initial values for each model were set to zero prior to solving. As mentioned in the consistency test section, the Standard GRG Nonlinear technique produced solutions that were less than the Standard Evolutionary techniques for May 2, 5, and 12. Before running the models, the Premium Solver™ convergence tolerances were changed from 0.0001 to 0.00000001. All models were run again and solutions recorded. The results can be seen in Appendix D. After tightening the convergence value, the May 2, 5, and 12 daily schedules all produced the same solutions provided by the Standard Evolutionary methods. The remaining schedules produced solutions identical to the first round of tests. All 26 daily schedules were run a third time and solutions recorded. In every case, the model produced solutions identical to the previous solution. It was concluded that the Standard GRG Nonlinear/Standard Simplex LP algorithm combination produces repeatable results.

Summary

This chapter fully described the problem, model, the type of data collected, and how it was analyzed. It also introduced the methods used to form the basis of the

analysis. The description of the model development and the mathematical formulations for each model stage was provided. Also presented were several techniques used to verify solutions produced by four Premium Solver™ algorithms. The Standard GRG Nonlinear Solver method was found to produce consistent and repeatable solutions in a fraction of the time required by the three Standard Evolutionary methods tested. As such, the Standard GRG Nonlinear method is used to solve stage one, while the Standard Simplex LP method is used in stage two of the research model. Chapter IV provides the results of the model and actual schedule comparisons, including the weighted sums, number of scheduled launch facilities, and manpower utilization rates. Sensitivity analysis of five different response times and supportable security umbrella quantities is performed. Sensitivity analysis results are compared to the original model solutions. Post analysis is performed to compare model solutions using straight-line distance calculations with actual F. E. Warren AFB security umbrella coverage information.

IV. Analysis

Introduction

This chapter discusses the results obtained by comparing the research model solutions to the actual maintenance activities performed between May 1 and May 26, 2005 at F. E. Warren AFB, WY. Analysis is performed on the weighted sum of launch facilities selected, number of open hole/penetrated launch facilities chosen for the daily schedule, and manpower utilization for both maintenance and security. A maximal covering location program (MCLP) algorithm is used for the two-stage heuristic model. Each stage utilizes Microsoft Excel® Premium Solver™ to compute optimal, or near optimal, model solutions. Sensitivity analysis is performed by changing the security umbrella response times, as well as by changing the number of supportable security umbrellas available. Post analysis is performed to consider the effects of using actual F. E. Warren AFB security umbrella coverage information on research model solutions.

Analysis Preparation

As summarized in Chapter III, the Standard GRG Nonlinear algorithm was found to produce consistent and repeatable solutions in a fraction of the time required by the three Standard Evolutionary methods tested. As such, the Standard GRG Nonlinear method is used to solve stage one of each model. Stage two is solved using the Standard Simplex LP method, due to its suitability for models that display characteristics of a linear model. This linear programming (LP) method is extremely accurate, fast, and produces a globally optimal solution in nearly every situation. Once the appropriate

Premium Solver™ algorithms were selected and the tolerance parameters adjusted, the research model was ready to generate solutions. The schedules of completed maintenance activities for May 1 through May 26 were reviewed for accuracy, total weighted sums for open hole and penetrated launch facilities were computed, and the number of completed open holes and penetrated launch facilities were calculated. This information served as the baseline data set to which the research model solutions were compared.

Model Assumptions

The following ten assumptions have been made with this research model:

1. Only open holes and maintenance activities requiring launch facility penetration are considered by the model;
2. Maintenance activities have the appropriate quantity/type of maintenance team, security personnel, and resources to be considered for scheduling;
3. Each team can perform maintenance at only one launch facility;
4. The response time matrix approximates actual response times;
5. Maintenance categories and weights are appropriately allocated;
6. The baseline maintenance schedules analyzed by the model are accurate reflections of actual maintenance performed from May 1-26, 2005;
7. F. E. Warren AFB utilized 2 security umbrellas with a 60-minute response time radius during this period;
8. Security escorts (SETS) dedicated to standby maintenance teams are unavailable;
9. Only Minuteman III maintenance activities are considered;
10. Security umbrellas do not shift or shrink as maintenance is completed;

A description of each assumption follows. 1. Maintenance activities that do not require presence of security forces personnel do not fall under the security umbrella concept, as no access is provided to the missile or critical weapon system components. This model is only concerned with maintenance activities affected by this concept. 2. All open hole and maintenance activities requiring launch facility penetration may be included in the daily schedule for consideration, but are excluded if the appropriate teams, parts, or equipment are not available to perform the maintenance. Experience has shown that including maintenance activities that cannot be performed will inappropriately weight the missile alert facilities that cover these sites. This can lead to poor model solutions. 3. In reality, certain maintenance teams can perform maintenance at more than one launch facility in one day; however, without prior knowledge of which teams were able to do so, the model in unable to correctly account for this situation. 4. Dawson (2005) developed the distance matrix using straight-line distance calculations. To compute the response time, the calculated distances were divided by 40 mph. This average speed limit attempts to account for maximum speed travel speeds of 65 mph on major highways, the 25 mph speed limit on gravel roads, and reduced travel speeds required during winter driving conditions. Though calculated distances are accurate, actual response times between every Minuteman III missile alert facility and launch facility would provide more accurate model solutions. 5. Maintenance categories and weights were constructed using methods described in Chapter III. Manipulating these factors could potentially produce better model solutions, but the effort and time required to do so is beyond the scope of this research. 6. The actual baseline daily schedules developed for this model are a culmination of data collected from the daily pre-schedules, daily status sheets, and work

order completion history only. Chapter III provides details on how discrepancies between data sets were considered. The IMMP system may have provided other launch facilities to be considered, but this could not accurately be determined with the data available. 7. The security umbrella concept allows for a maximum of 2 security umbrellas with a 60-minute response time; as such, this is the standard used when comparing the baseline schedule and model solutions. 8. Standby maintenance teams are available for unscheduled, high-priority maintenance requirements. SETS dedicated to these teams are subtracted from the pool of available security personnel. 9. Security personnel allocated to Peacekeeper maintenance activities are subtracted from the pool of available security personnel. 10. Once established, security umbrellas do not shift to new locations as scheduled maintenance activities are completed.

Initial Observations

The model solutions for the first nine schedules were compared to the actual baseline maintenance schedules to measure model effectiveness. Although the research model's weighted sum solutions were as good as, or better than, the actual daily schedule solutions, problems were discovered with the type of maintenance activities being selected by the model. In two instances, the weighted sum of several low-priority categories exceeded the weight of a higher-priority category. In order to meet the published objective of a maintaining a maximum number of ICBMs on full alert status, the maintenance categories and applied weights had to be readdressed. With the help of an experienced missile maintenance senior noncommissioned officer, the maintenance categories were realigned to more accurately reflect missile maintenance objectives and

priorities. The top three maintenance category weights have the greatest impact on achieving the published objective. As such, the existing weights of these categories were multiplied by a factor of three. Doing this provided a greater level of separation between the three mission-critical categories and the lower-priority maintenance categories to ensure that a large number of low-priority tasks would not override a critical task.

Analysis Method

This analysis first compares the results obtained from the research model to the actual maintenance schedule. All results are based on a 60-minute response time and 2 supportable security umbrellas. Data sets compared include total weighted sums, number of open holes/penetrated launch facilities, and security personnel/maintenance team utilization. Appendix E displays the complete comparison of this data. Figure 2 compares the number of completed launch facilities in the actual schedule versus the model solution.

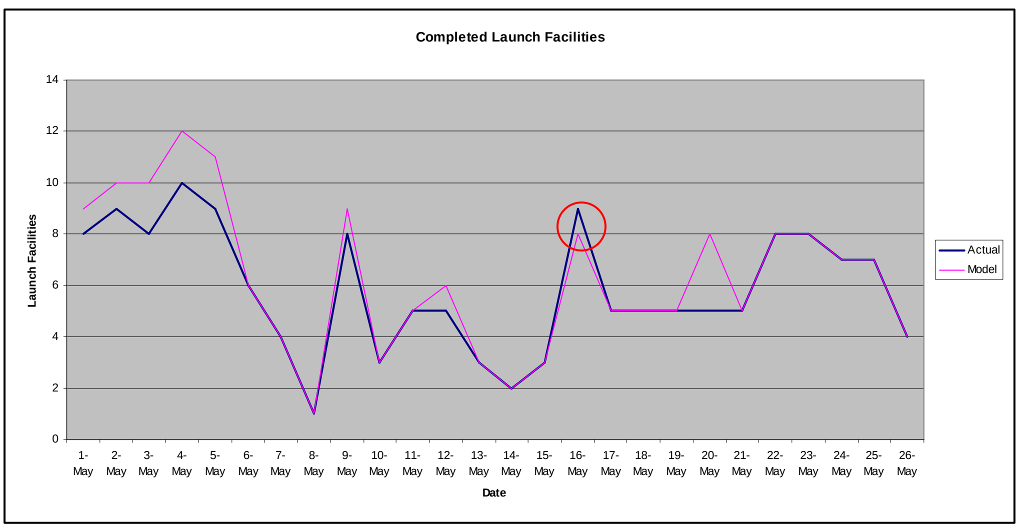


Figure 2. Completed Launch Facilities: Actual vs. Model

In 16 of the 26 days analyzed, the research model solution selected more launch facilities than was completed in the actual baseline schedule. For 9 days, the model and actual schedule results were identical. On May 16, the actual schedule completed one more launch facility than the model solution produced. This area is circled in Figure 2. As the graph indicates, research model solutions are a slight improvement over the actual baseline schedule. Improvements ranged from one to three additional scheduled launch facilities per day; however, the overall average improvement for the 26 days analyzed was approximately 1 launch facility per day.

Table 6 compares the total weighted sums produced by the actual baseline schedule and the research model. Total model improvements over the actual schedule are offered, as well as the percentage improvement realized by the model solutions.

Table 6. Weighted Sums: Actual vs. Model

May	Actual	Model	Model Improvement	Percent Improvement
1	524	540	16	3.05%
2	657	673	16	2.44%
3	662	753	91	13.75%
4	294	367	73	24.83%
5	300	358	58	19.33%
6	665	686	21	3.16%
7	75	75	0	0.00%
8	27	27	0	0.00%
9	1165	1192	27	2.32%
10	200	200	0	0.00%
11	202	213	11	5.45%
12	208	234	26	12.50%
13	88	99	11	12.50%
14	32	43	11	34.38%
15	66	82	16	24.24%
16	836	853	17	2.03%
17	215	226	11	5.12%
18	268	268	0	0.00%
19	1590	1590	0	0.00%
20	174	230	56	32.18%
21	131	131	0	0.00%
22	216	238	22	10.19%
23	1325	1325	0	0.00%
24	137	165	28	20.44%
25	473	495	22	4.65%
26	797	797	0	0.00%
Average	436	456	20.5	8.94%

In 18 of the 26 days analyzed, the research model produced a greater total weighted sum than the actual schedule. For 8 days, the model and actual schedule results were identical. The model's weighted sum improvements ranged from 11 to 91 points. On average, the research model produced a weighted sum that was 20.5 points higher than the actual schedule, which equates to an average improvement of 8.94 percent. This would be equivalent to adding an additional periodic maintenance activity to the daily schedule each day.

Figure 3 shows the total number of SETS used for the actual baseline schedule and research model, as compared to the number of SETS available.

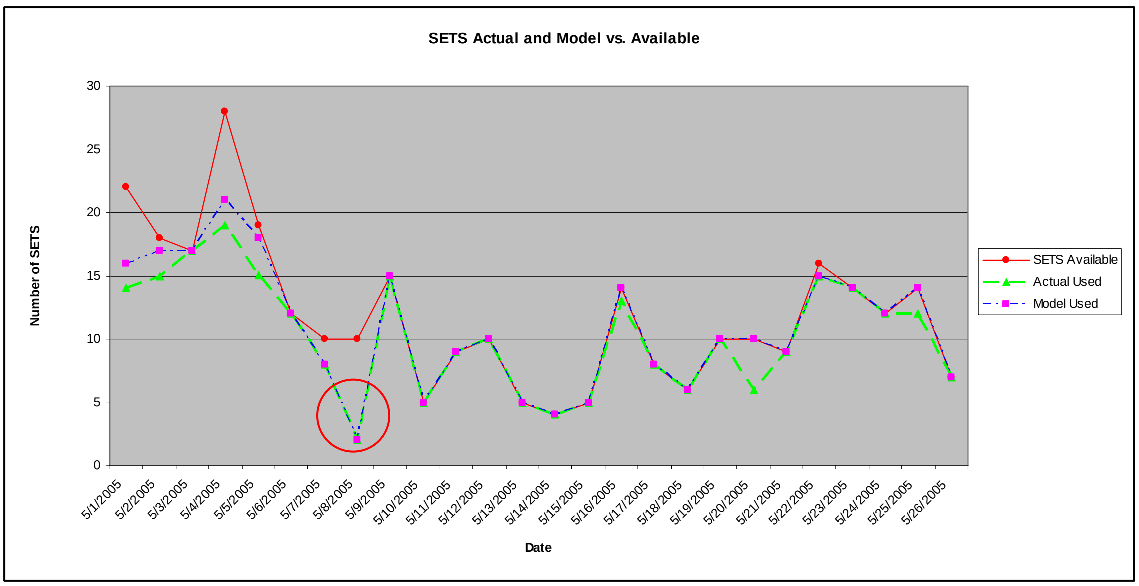


Figure 3. Security Escort Utilization: Actual and Model vs. Available SETS

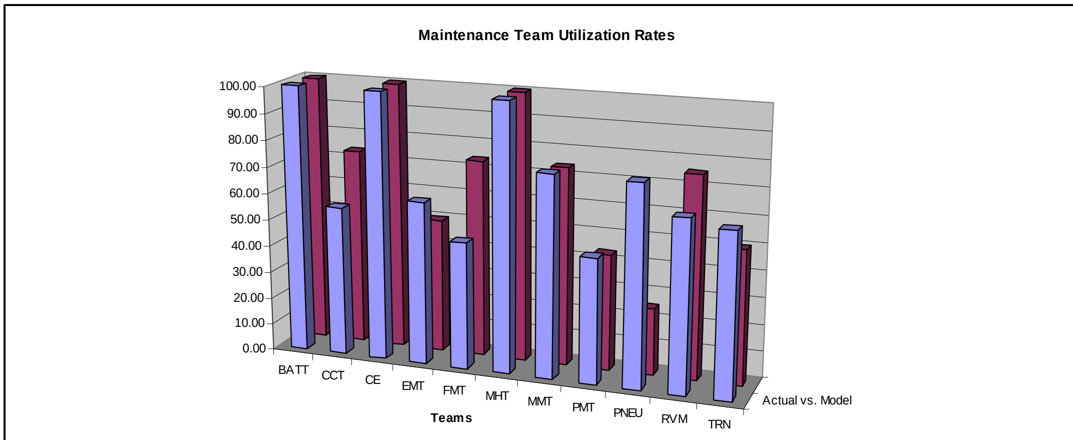
As the line graph indicates, not all SETS that were made available daily were actually used by either model. The area circled on the graph indicates that significantly more SETS were made available on Sunday, May 8, than were used by either model. This

correlates with the reduction observed on May 8 in Figure 2. On that particular day, only one launch facility was scheduled for maintenance and only three teams were built into the schedule, two of which were priority-one standby teams. Situations like this were few in the May data, but should be discussed by maintenance and security forces managers to eliminate future reoccurrence and the associated lost opportunity for maintenance.

The actual baseline schedule had an average SETS utilization rate of 90.03 percent, while the model solution produced a 94.11 percent utilization rate. The SET availability numbers used in this graph accounted only for the escorts made available to work Minuteman III launch facilities. SETS assigned to a Peacekeeper launch facility were subtracted from the total available personnel. Additionally, SETS dedicated to a standby maintenance team were removed from the original total, as they are not readily available for use by other maintenance teams.

The utilization of other guards is not shown. The "Other Guards" category is made up of camper teams, open-hole security teams, reentry system security teams, and fire teams made available for specific maintenance activities. The actual schedules averaged a 99.41 percent utilization rate of these security personnel as they were made available. The model solutions used 100 percent of the provided security forces personnel.

Missile maintenance team utilization rates for both the actual schedule and research model were compared. The utilization rates were calculated for each of the eleven maintenance teams. The results are provided in Figure 4.



	BATT	CCT	CE	EMT	FMT	MHT	MMT	PMT	PNEU	RVM	TRN
Actual vs. Model	100.00	55.88	100.00	60.90	47.44	100.00	75.26	46.67	75.00	64.04	61.11
Model Rates	100.00	73.53	100.00	50.00	73.72	100.00	73.95	43.33	25.00	75.44	50.00

Actual vs. Model ■ Model Rates

Figure 4. Maintenance Team Utilization Rates

As shown in the data table above, both the actual schedule and research model solutions utilized Battery teams, Civil Engineering teams, and Missile Handling Teams every day they were available to perform maintenance. The actual schedule focused on maintenance activities requiring the talents of the Electro-Mechanical Teams, Periodic Maintenance Teams, Pneudraulics teams, and Training teams. The research model schedules focused on maintenance activities requiring the expertise of the Corrosion Control Teams, Facilities Maintenance Teams, and Rivet Mile teams. In both models, the Periodic Maintenance Teams were selected to perform maintenance less than 50 percent of the days that they were available, which indicates that managers should look at this lower-priority maintenance task more closely for scheduling improvement opportunities.

Figure 5 summarizes the overall daily weighted sum improvements that were produced by the research model.

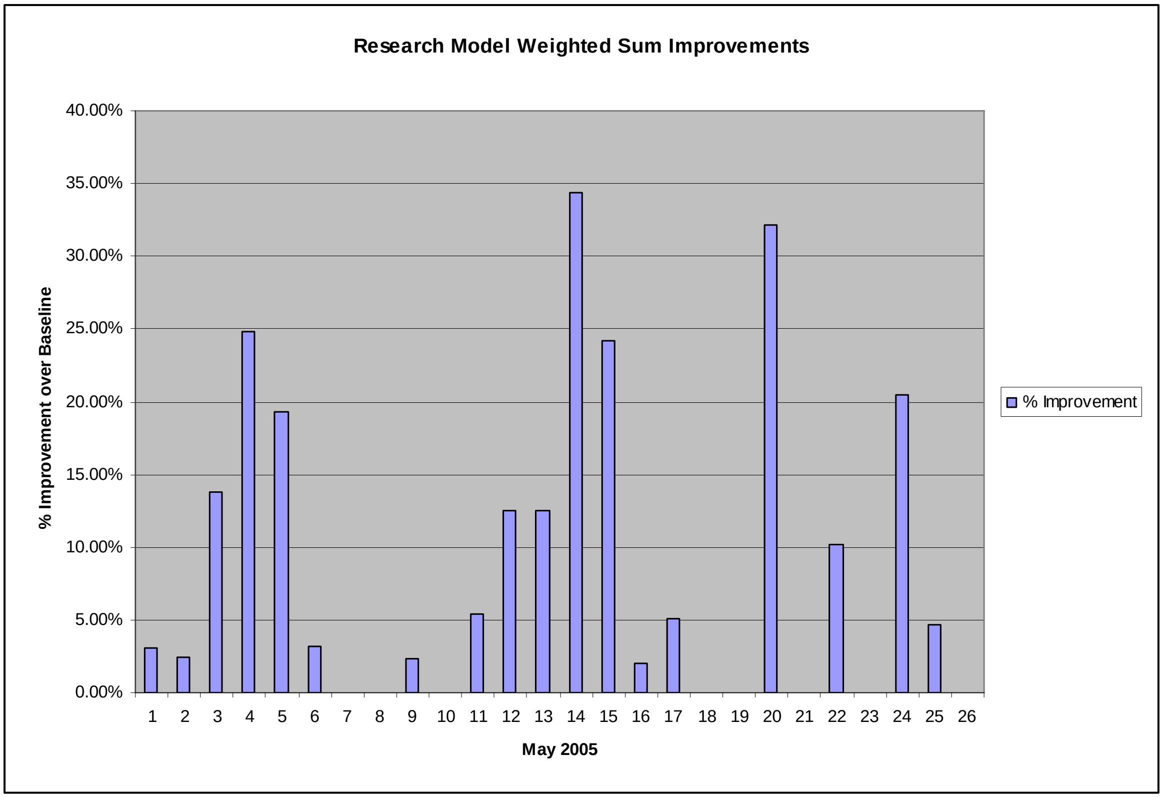


Figure 5. Model Improvements Over Actual Schedule

As the graph illustrates, improvements were realized in 18 of the 26 daily schedules, and ranged between 2 and approximately 35 percent. As this research has demonstrated, implementing a software solution within missile maintenance scheduling can enhance current methods used to develop daily missile maintenance schedules.

Sensitivity Analysis

Each of the 26 maintenance schedules was run several more times for the purposes of sensitivity analysis. The first sensitivity analysis model set alters the security force response times from 60 minutes to 20 minutes, in 10-minute increments, to show the effects on the total weighted sum of maintenance activities, the number of launch

facilities that are scheduled, and maintenance team/security personnel utilization. All other parameters remain unchanged in this analysis to isolate the effects of attenuated security umbrellas. From this analysis, missile maintenance and security forces managers can visualize how various response times will affect the total maintenance effort.

The second sensitivity analysis model set adjusts the number of supportable security umbrellas, ranging from one to five total umbrellas. The response time parameters are also adjusted, as in the first sensitivity analysis models, to observe the effect of response time on the number of security umbrellas required to achieve the optimal solution. Also provided are the response time/security umbrella combinations that produced the best model solutions for each daily schedule. The results of this analysis will help managers visualize the effects of various security levels on the amount of maintenance activities able to be accomplished.

Security Response Time Sensitivity Analysis.

The complete sensitivity analysis for response time impacts on the weighted sums of daily scheduled maintenance activities, as well as the total number of scheduled launch facilities, can be found in Appendix F. Appendix G provides detailed information regarding the impacts of these response time changes on maintenance team and security personnel utilization rates. Table 7 summarizes the impact of reduced response times on weighted sums of scheduled maintenance activities.

Table 7. Weighted Sums vs. Response Times

May	Weighted Sum vs. Response Time				
	60	50	40	30	20
1	540	506	497	497	460
2	673	657	621	615	578
3	753	753	651	553	434
4	367	340	319	298	276
5	358	306	306	306	269
6	686	686	686	670	622
7	75	75	75	75	43
8	27	27	27	27	27
9	1192	1181	1171	1021	942
10	200	200	200	200	200
11	224	213	224	224	171
12	234	218	218	218	187
13	99	99	99	88	99
14	59	59	59	59	43
15	82	82	82	82	77
16	874	874	863	842	763
17	248	248	248	242	216
18	268	268	234	234	234
19	1590	1590	1494	1494	1446
20	220	220	220	186	186
21	131	131	115	115	115
22	238	238	206	195	174
23	1325	1325	1309	1293	1251
24	165	165	154	132	85
25	495	495	495	458	400
26	797	797	797	797	426
Average	458	452	437	420	374
Avg Decrease		1.40%	4.61%	8.38%	18.42%

The response time radius and weighted sums are positively correlated; the weighted sum totals increase as the security umbrella radius increases. As Table 7 indicates, the 60-minute response time provided an average weighted sum of 458. The differences in weighted sums from the 60-minute to 30-minute response times indicate that reducing the security umbrella size has minimal impact on the type and quantity of maintenance activities performed. However, reducing the security response times to 20 minutes appears to have a significant impact on the weighted sum of activities that can be performed, with average weighted sums decreasing by over 18 percent.

Only a slight decrease in weighted sums is noticed between the first four increments, with a larger total decrease of 84 points observed with the 20-minute response time. This large decrease at 20 minutes is equivalent to 1 high-priority maintenance activity or several low-priority activities. The small decrease in weighted

sums from the 60-minute umbrellas to the 30-minute umbrellas is attributable to the small number of maintenance activities available for the schedule, as well as the maintenance schedulers' abilities to tightly cluster scheduled maintenance activities. With the 20-minute umbrellas, it is apparent that due to the geographic spacing of available jobs, the two umbrellas are only able to cover the closest, high-priority maintenance activities. Extensive geographic clustering efforts would be required to cover more maintenance activities within these small umbrellas.

Comparisons were also made between the actual schedule and research models regarding the effects of adjusting the security umbrella response times on the number of launch facilities selected for the schedule. Figure 6 illustrates the impact of adjusting security response time constraints on the number of launch facilities scheduled daily.

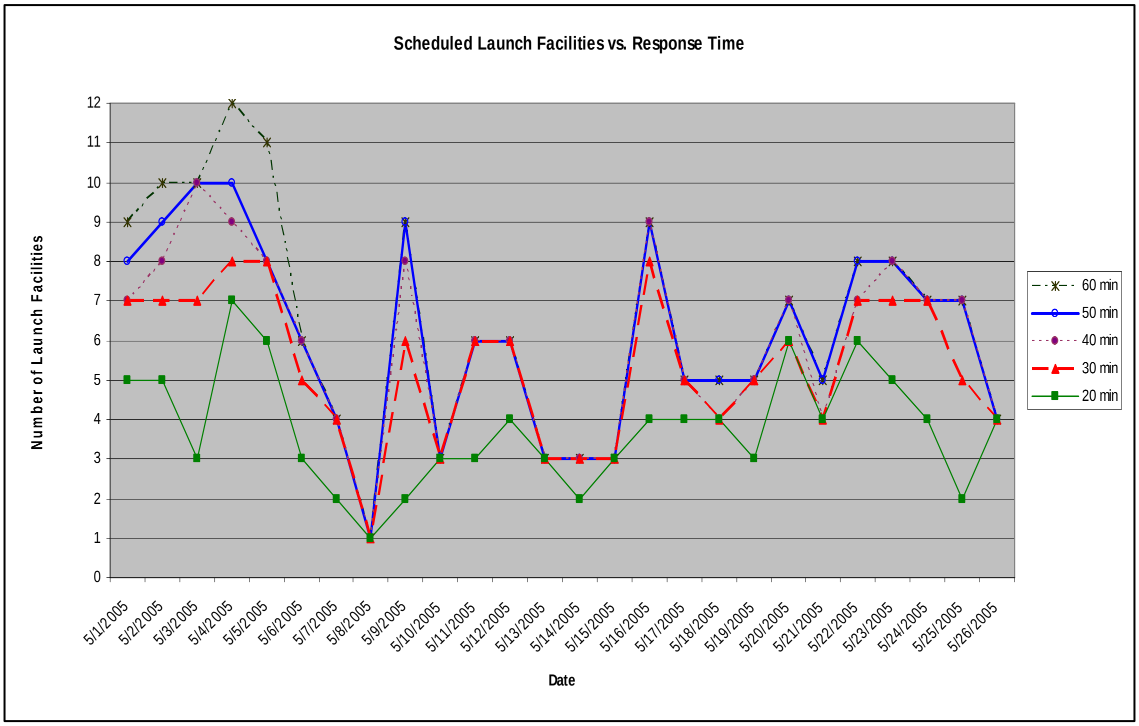


Figure 6. Response Times vs. Total Scheduled Launch Facilities

The separation between the 60, 50, and 40-minute response times appear drastic in the first few days, but then they remain close through the remainder of the month. The 30-minute response time also tracks with the previous three response times, but more significant decreases are observed throughout the graph. The 20-minute response time obviously has the greatest impact, with large, steady reductions in scheduled launch facilities observed over the entire month of May. The 60, 50, and 40-minute response times all averaged 6 scheduled launch facilities daily, while the 30 and 20-minute response times averaged 5 and 4 scheduled launch facilities, respectively.

The following six figures illustrate how different security umbrella response times affect the maintenance activities that are performed. Figure 7 is a depiction of the F. E. Warren AFB missile complex with all candidate launch facilities identified.

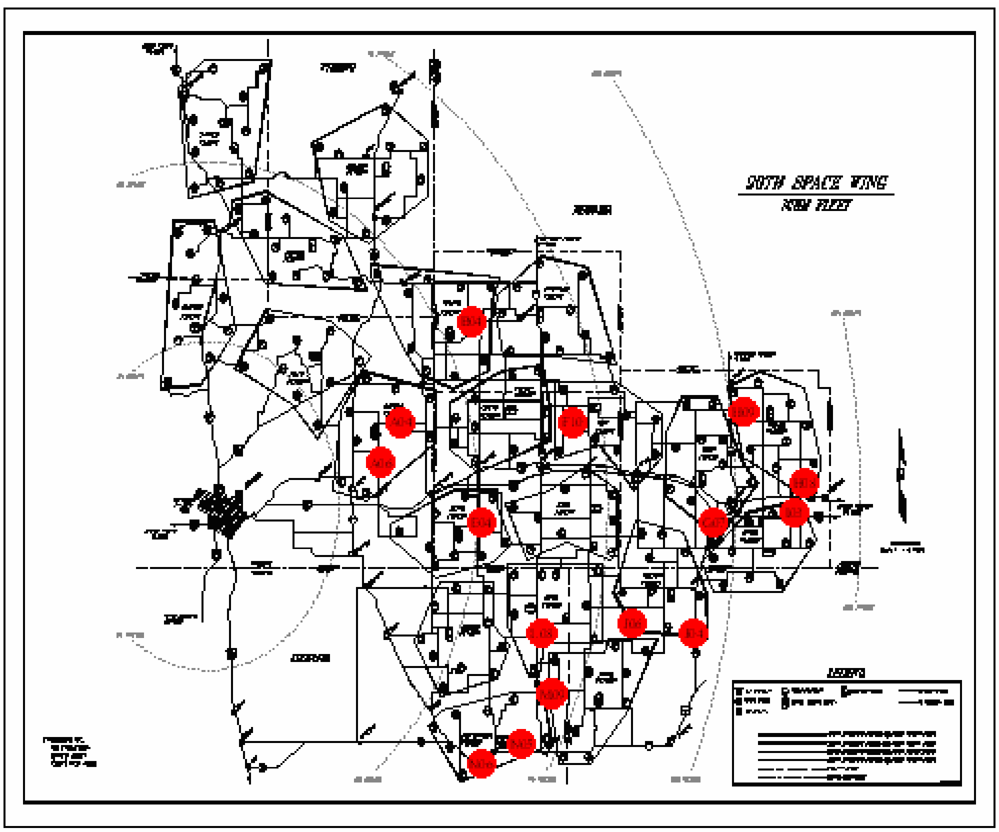


Figure 7. Candidate Launch Facilities for May 9, 2005 Schedule

All launch facilities are dispersed throughout the F. E. Warren AFB missile complex, comprising 12,600 square miles of Wyoming, Nebraska, and Colorado. The research model uses constraints of the maintenance teams and security personnel, the maximum security response time, and quantity of security umbrellas to select a solution set from the candidate launch facilities.

Figure 8 illustrates the solution set selected by the model for May 9, 2005.

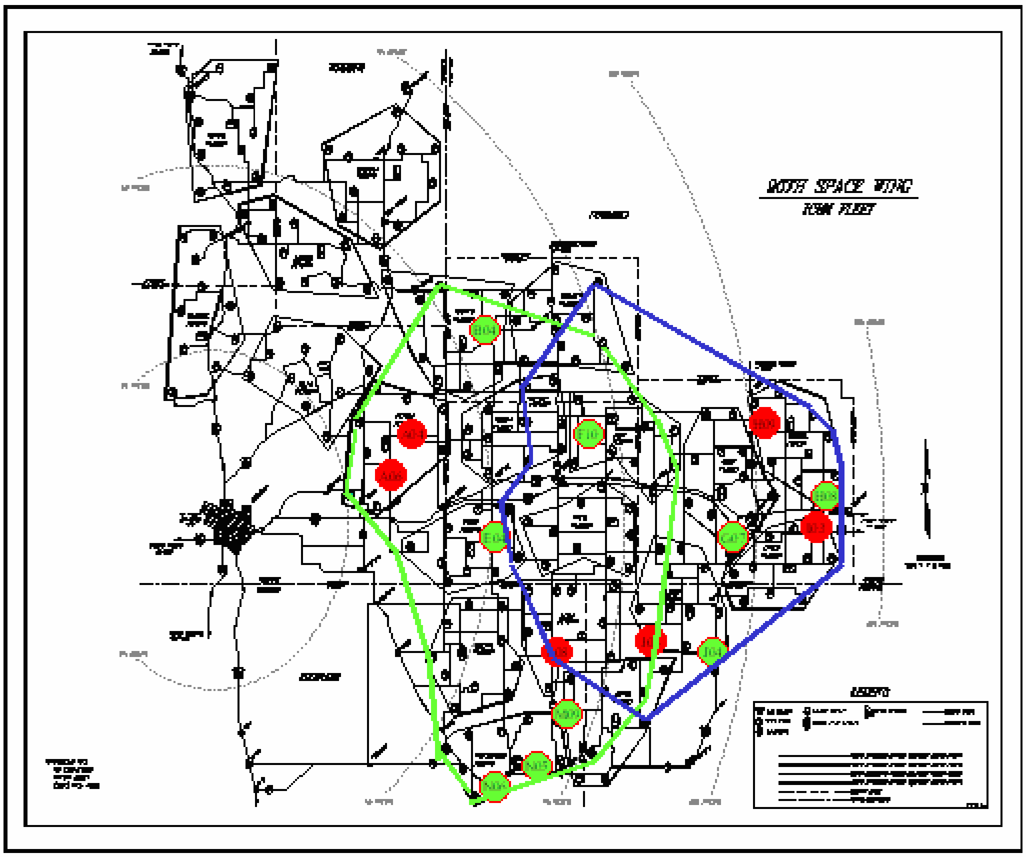


Figure 8. Scheduled Maintenance Under 60-Minute Umbrellas

This particular date was chosen for illustration because a Limited Life Component (LLC) and Off-Alert maintenance activity were included in the candidate set. Both are important because they greatly impact the mission, require significant amounts of pre-

maintenance coordination, and also require a large number of additional guards to perform each task. In this figure, both umbrellas have a 60-minute response radius and were built using data contrived from the model's distance matrix. The umbrella with the light border is centered on missile alert facility E-01. The umbrella outlined with a dark border is centered on missile alert facility G-01. The nine lightly shaded circles represent the launch facilities that comprise the model solution set, while the dark circles have been excluded. The total weighted sum for this solution is 1192. The utilization rate for security personnel is 100 percent, while the utilization rate of maintenance teams is 86.6 percent. Both high-priority maintenance activities are included in the solution set.

In Figure 9, both security umbrella response radii have decreased to 50 minutes.

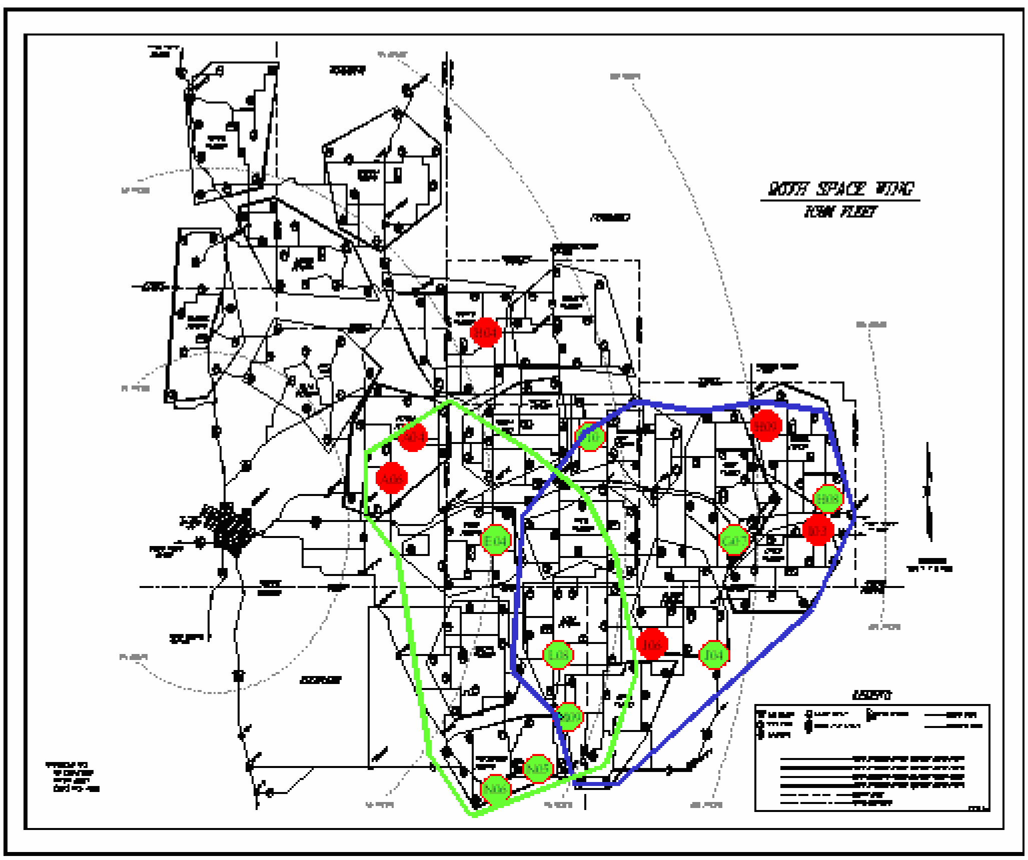


Figure 9. Scheduled Maintenance Under 50-Minute Umbrellas

In this figure, the umbrella with the light border has shifted to missile alert facility J-01. The umbrella with the dark border is now centered on missile alert facility O-01. Nine launch facilities have still been selected as part of the solution set, but the security umbrellas have shifted to the missile alert facilities that produce the largest weighted sum of candidate launch facilities, given the decrease in response time. The total weighted sum for this solution decreased from 1192 to 1181. The utilization rate for security personnel is still 100 percent, while the utilization rate of maintenance teams remains unchanged at 86.6 percent. Both high-priority maintenance activities are included in the solution set.

In Figure 10, both umbrella response time radii have decreased to 40 minutes.

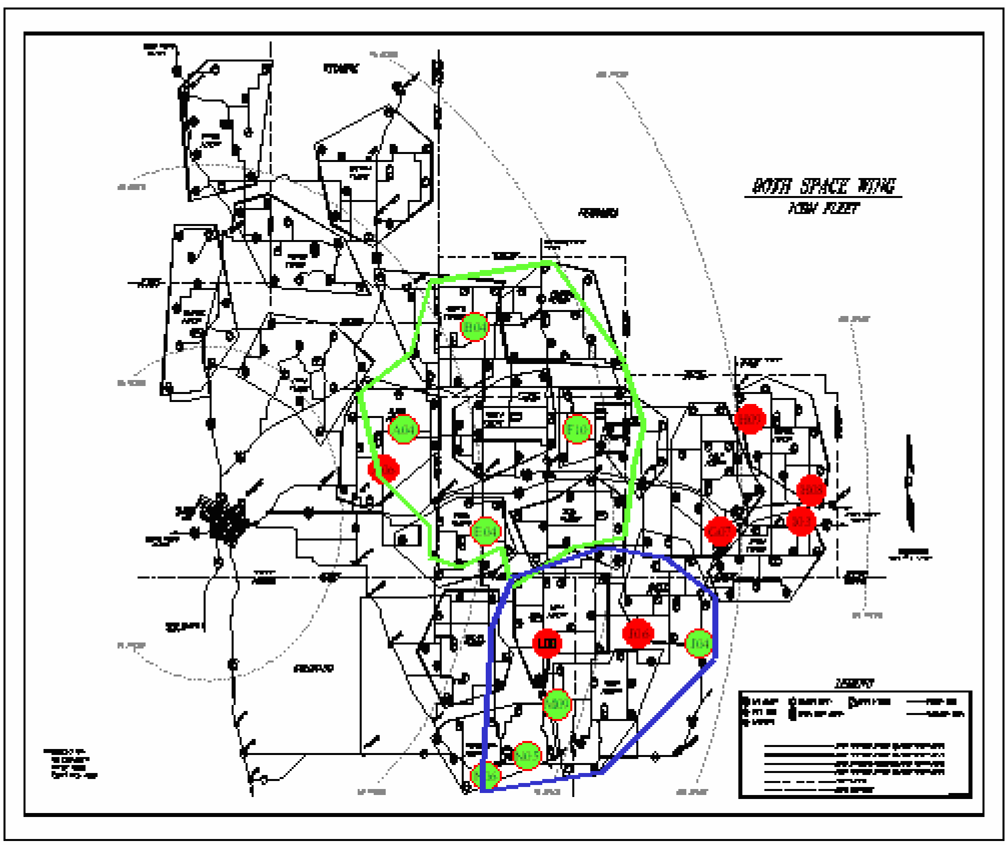


Figure 10. Scheduled Maintenance Under 40-Minute Umbrellas

In this figure, the umbrella with the light border has shifted to missile alert facility D-01. The umbrella with the dark border is now centered on missile alert facility M-01. Eight launch facilities have now been selected as part of the solution set, as the security umbrellas have again shifted to the areas with the highest concentration of higher-priority maintenance activities. The total weighted sum for this solution decreased from 1181 to 1171. The utilization rate for security personnel remains at 100 percent, but the maintenance team utilization rate has decreased from 86.6 percent to 80 percent. Both high-priority maintenance activities are still included in the solution set.

In Figure 11, the response time radius of both security umbrellas has now decreased to 30 minutes.

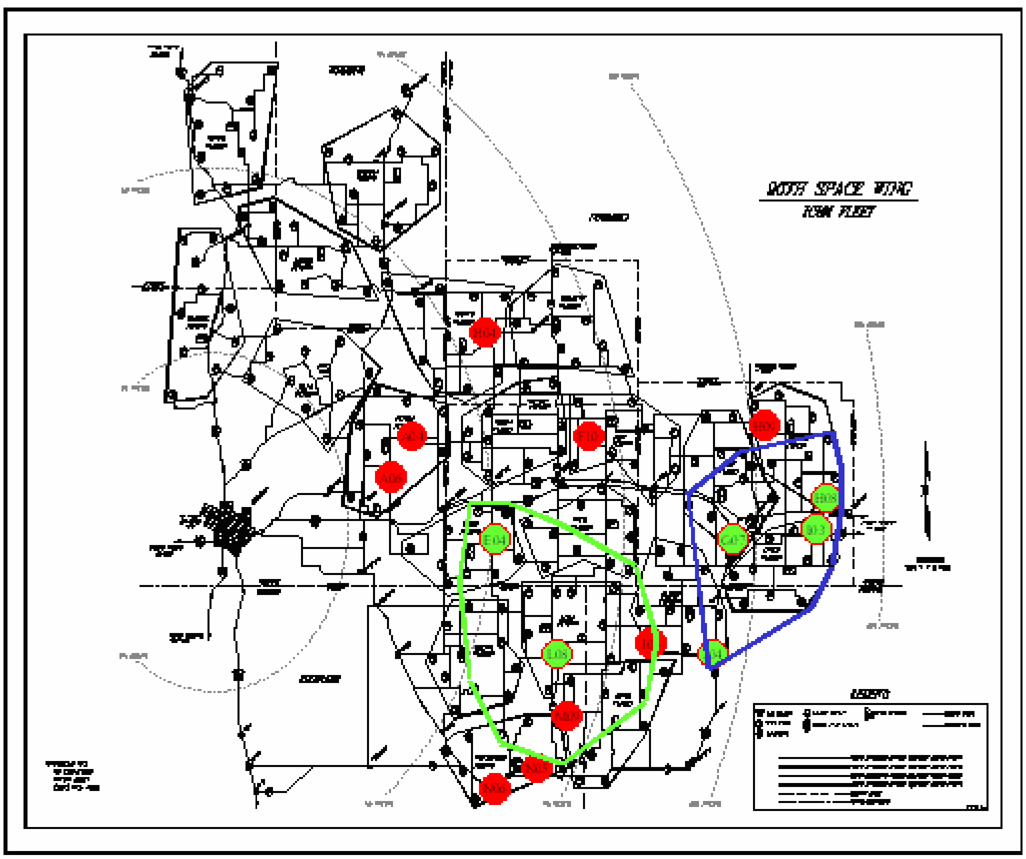


Figure 11. Scheduled Maintenance Under 30-Minute Umbrellas

In this figure, the umbrella with the light border has shifted again, now centered on missile alert facility I-01. The umbrella with the dark border has centered on missile alert facility L-01. The number of solution set launch facilities has decreased to six. The total weighted sum for this solution decreased from 1171 to 1021. The utilization rate for security personnel has dropped to 94 percent, while the maintenance team utilization rate has decreased to 66.67 percent. Security umbrellas have again shifted to cover both high-priority maintenance activities. The two launch facilities shaded dark within the lightly-shaded umbrella cannot be scheduled, as the appropriate maintenance teams are scheduled to work higher-priority maintenance activities.

In Figure 12, the radius of both security umbrellas has decreased to 20 minutes.

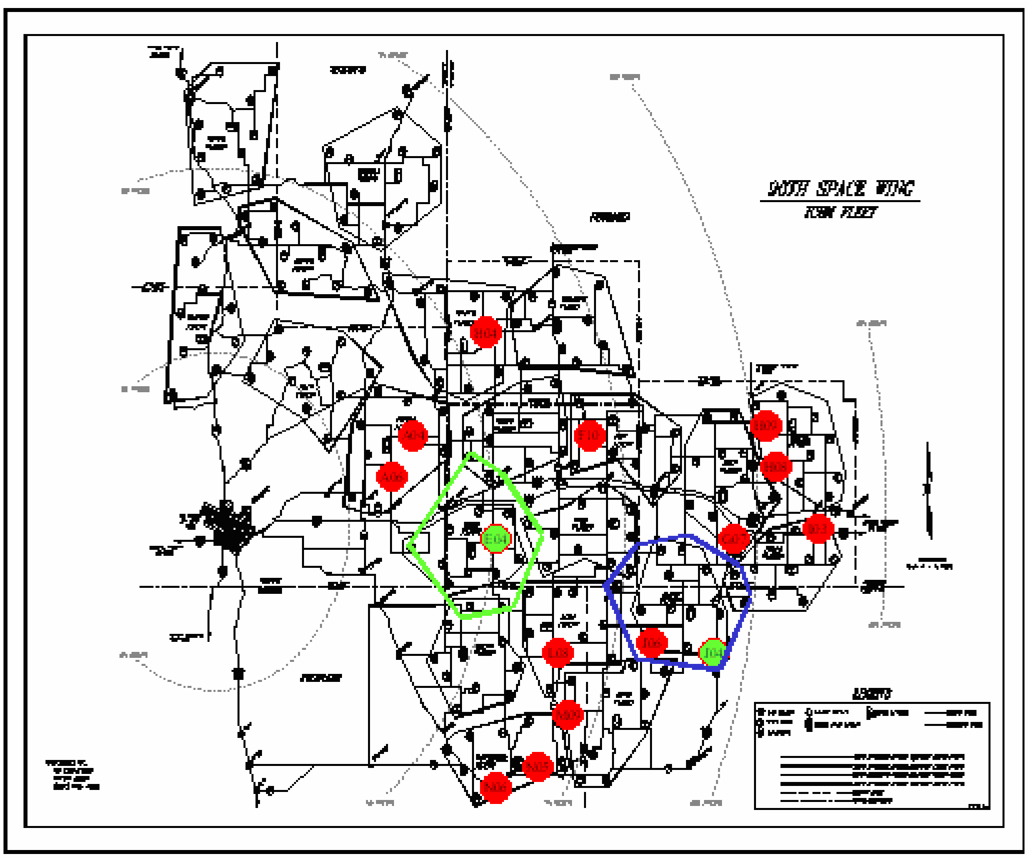
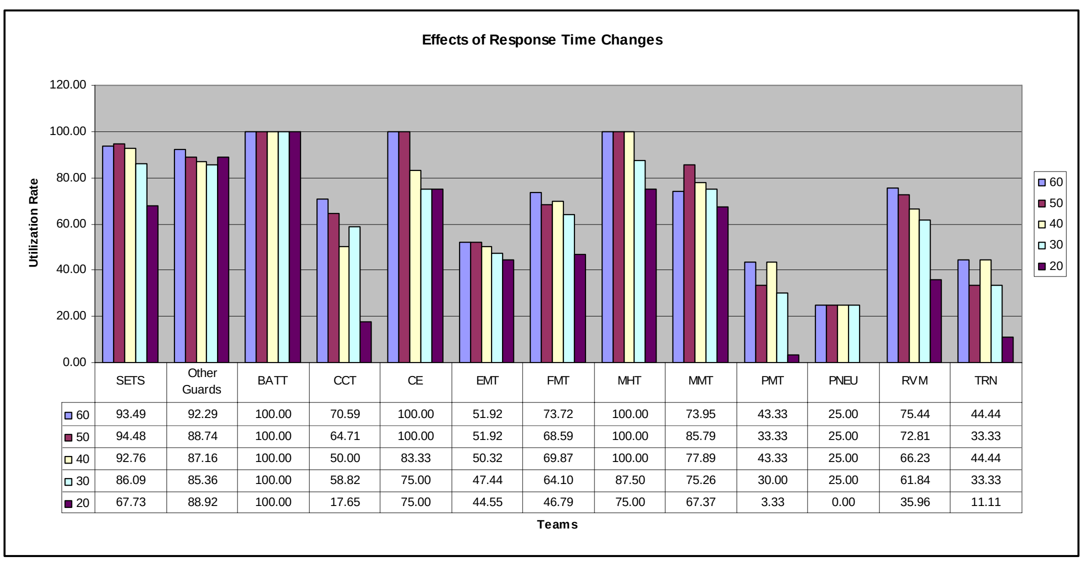


Figure 12. Scheduled Maintenance Under 20-Minute Umbrellas

Both security umbrellas are centered on the only two missile alert facilities that encompass the two highest-priority launch facilities, the LLC and the Off-Alert maintenance action. The umbrella with the light border is centered on missile alert facility E-01 and the umbrella with the dark border has centered on missile alert facility J-01. Only two of the original nine scheduled launch facilities remain in the solution set. The total weighted sum for this solution has decreased from the original 1192 to 942. The utilization rate for security personnel has dropped to from 100 percent to 78.9 percent, while the maintenance team utilization rate has plummeted to 40 percent. As can be seen in the previous five figures, reducing the security response time can drastically impact an organization's ability to perform maintenance. If maintenance activities within the daily schedule are not geographically clustered, it will be difficult to maximize maintenance efforts and improve manpower utilization rates.

Figure 13 examines the impact of reduced response times on personnel usage. The complete calculations for each individual team can be found in Appendix G.



	SETS	Other Guards	BATT	CCT	CE	EMT	FMT	MHT	MMT	PMT	PNEU	RVM	TRN
60	93.49	92.29	100.00	70.59	100.00	51.92	73.72	100.00	73.95	43.33	25.00	75.44	44.44
50	94.48	88.74	100.00	64.71	100.00	51.92	68.59	100.00	85.79	33.33	25.00	72.81	33.33
40	92.76	87.16	100.00	50.00	83.33	50.32	69.87	100.00	77.89	43.33	25.00	66.23	44.44
30	86.09	85.36	100.00	58.82	75.00	47.44	64.10	87.50	75.26	30.00	25.00	61.84	33.33
20	67.73	88.92	100.00	17.65	75.00	44.55	46.79	75.00	67.37	3.33	0.00	35.96	11.11

Figure 13. Impact of Reduced Response Times on Personnel Utilization

Reducing the response time from 60 minutes to 30 minutes appears to have a limited effect on personnel usage. Civil Engineering felt the greatest reduction, with a 25 percent drop in team utilization. Several teams, such as the Battery and Pneudraulics teams, saw no change in team usage. The effects of the 20-minute response time had more drastic impacts on total maintenance team utilization, with reductions ranging from 0 percent for the Battery teams, to nearly 53 percent for Corrosion Control. The overall average utilization rate decreased by 25.6 percent for maintenance teams, while security forces personnel averaged a 14.57 percent reduction. In summary, as the security umbrella response radius decreases, daily schedules tend to utilize more maintenance teams that work on the higher-priority maintenance activities.

If actual travel times were substituted for the geographical distance method used to calculate response times, the results provided from the first set of sensitivity models might prove less optimistic. As discussed in Dawson (2005), the geographical distance method calculates distances based on location coordinates. This direct-path method does not consider that maintenance and security teams may have to travel several miles out of the way to reach a destination. Regardless, there is no perfect substitute for actual travel time. Because actual travel times between all missile alert facilities and all launch facilities are not currently available, the geographic Dawson (2005) distance matrix was used in this research. The results of the first sensitivity analysis only provide a general idea of how reduced response times could impact the missile maintenance mission. Figure 14 illustrates the May 9, 2005 research model launch facility solution previously identified in Figure 8. However, this solution set is now outlined with the actual 60-minute security umbrellas currently being employed at F. E. Warren AFB.

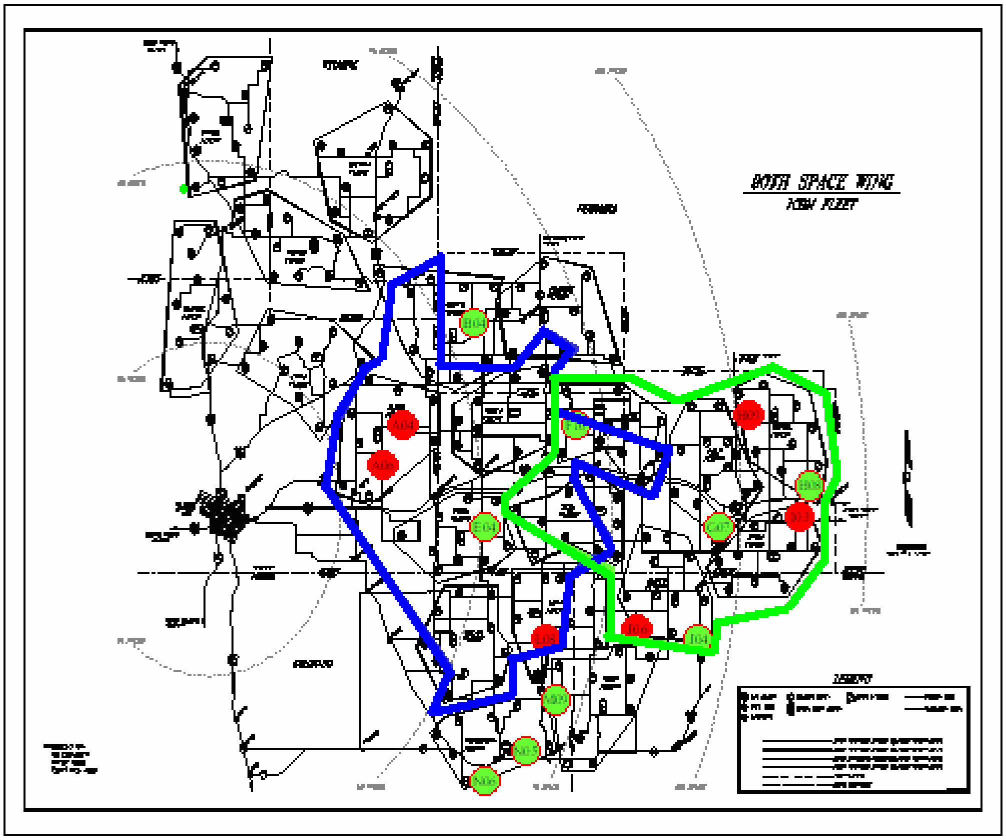
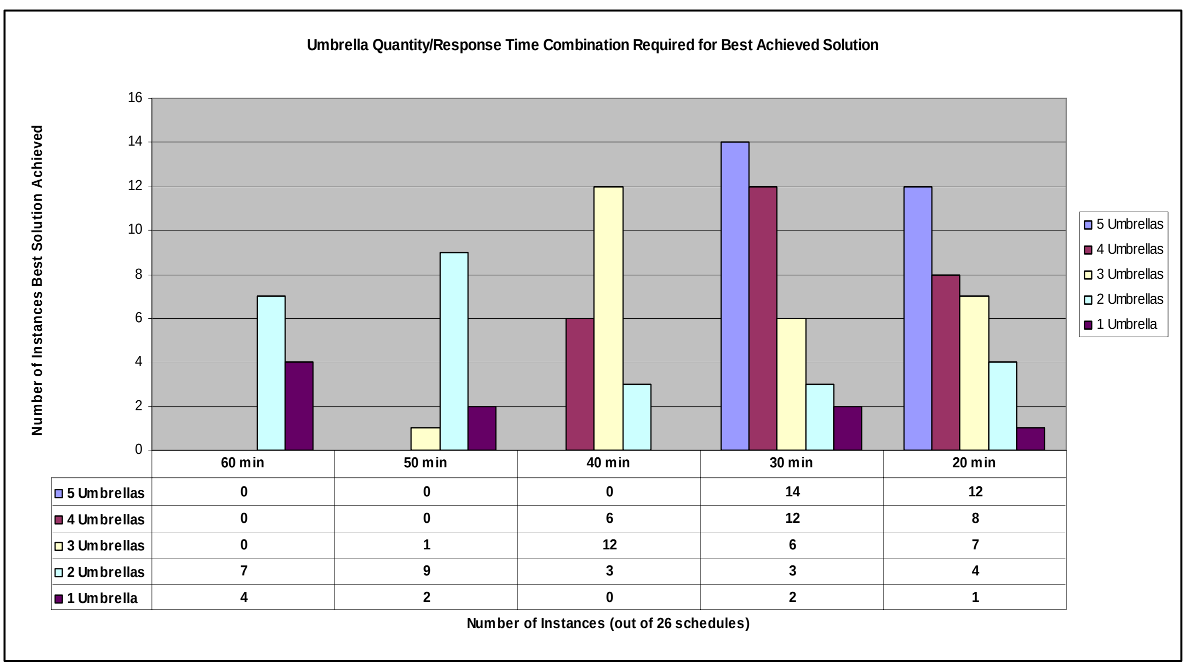


Figure 14. Actual 60-Minute Response Umbrella with Model Solution

The actual 60-minute security response E-01 and G-01 umbrellas employed by F. E. Warren AFB have been placed over the research model solution set. The lightly shaded circles identify the launch facilities included in the research model solution set for a 60-minute response time. The E-01 and G-01 umbrellas derived from the original distance matrix covered all nine launch facilities, as was seen in Figure 8. However, the security umbrellas used by F. E. Warren AFB, which are based on actual travel time, have eliminated four of these launch facilities. This fact identifies a limitation of the research model when using geographical distance calculations, but does not hinder its ability to reveal potential effects of constraint changes on the maintenance mission. The research model could easily be modified to use real driving times if they were made available.

Impacts of Adjusting Security Umbrella Constraints.

This analysis examines how adjusting the security umbrella quantity constraint affects the weighted sums of daily scheduled maintenance, as well as the number of scheduled launch facilities. The number of permitted umbrellas within the model is setup as a “less than, or equal to,” constraint, with the maximum allowable security umbrellas establishing the upper bound. The complete results for the second sensitivity analysis can be found in Appendix H. The security umbrella quantity constraint was varied between 1 and 5, in increments of 1, while solutions for all 26 daily schedules were computed at each increment. For each umbrella quantity, the minimum response time required for each daily schedule to reach the best-achieved model solution was recorded. Figure 15 provides a breakdown of the minimum response time required to achieve the optimal weighted sum solution for each daily schedule.



	60 min	50 min	40 min	30 min	20 min
5 Umbrellas	0	0	0	14	12
4 Umbrellas	0	0	6	12	8
3 Umbrellas	0	1	12	6	7
2 Umbrellas	7	9	3	3	4
1 Umbrella	4	2	0	2	1

Figure 15. Minimum Response Time Required to Reach Best-Achieved Solution

The first row of the table illustrates that with the model security umbrella constraint set to five, 14 of the 26 daily schedules could achieve the best solution with a 30-minute response time, while the remaining 12 daily schedules only required a 20-minute response time to reach the best-achieved solution. In essence, with 5 security umbrellas in place, all 26 daily schedules could achieve near-optimal solutions with a 30-minute response time or less. As the umbrella constraint tightens, it appears that a negative correlation exists between the number of security umbrellas utilized and the minimum response time required to achieve the best achieved solution. As the quantity of umbrellas decreases from five to one, the minimum response times required for all 26 daily schedules to achieve the best solution increases from 30 minutes to 60 minutes. With the model constraints set to one security umbrella, only 9 of the 26 daily schedules could reach the best-achieved model solution; all other schedule solutions were less than optimal. In one instance, optimality could be achieved with 1 umbrella and a 20-minute response time. This is because only one launch facility was scheduled for that particular day and it was in close proximity of the security umbrella center. In 2 instances, optimality was achieved at 30 minutes and 1 umbrella. For these particular dates, 4 or less launch facilities were tightly clustered within 30 minutes of the missile alert facility serving as the umbrella center. However, these were isolated occurrences, as only 9 of the 26 schedules could even achieve optimality with 1 security umbrella established.

During analysis, it was found that in the majority of cases involving four or five security umbrellas, the model did not fully utilize the number of umbrellas allotted. This was especially true when 50 and 60-minute response times were established. As such, sensitivity analysis demonstrates that utilizing more than three umbrellas centered upon

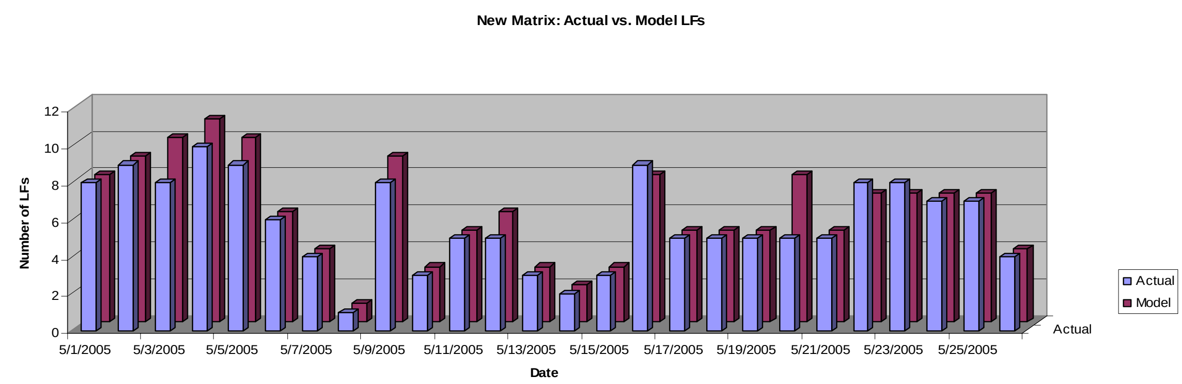
missile alert facilities would be wasting the additional security personnel required to support the unneeded umbrellas. However, as shown in Dawson (2005), if other locations in addition to missile alert facilities were considered, more than three security umbrellas could be better utilized. In conclusion, it is evident that in all 26 cases, a combination of 60-minute response radius and 2 established security umbrellas are sufficient to maximize the weighted sum of available daily maintenance activities. This parallels with the security umbrellas concept of operations currently being employed at F. E. Warren AFB. However, utilizing the third umbrella would allow for a 50-minute response radius and still maximize the weighted sum of maintenance activities performed.

Post Analysis

To address the limitations of geographical distance calculations used in the research model, the original response time matrix was altered. Each of F. E. Warren AFB's 15 security umbrella coverage maps, which are based on actual travel times, were examined closely to discover which launch facilities fell within the mandatory 60-minute radius. This data was translated into binary code and entered into the response time matrix; a one represents a launch facility that is covered by a specific security umbrella, while a zero represents a launch facility falling outside of the 60-minute radius.

Each of the 26 daily schedules was analyzed once more using the research model with the modified response time matrix. The number of scheduled launch facilities and weighted sum of the model solution and actual schedule were compared. The complete

results of this analysis can be found in Appendix I. Figure 16 compares the number of launch facilities scheduled by the model versus the actual maintenance schedule.

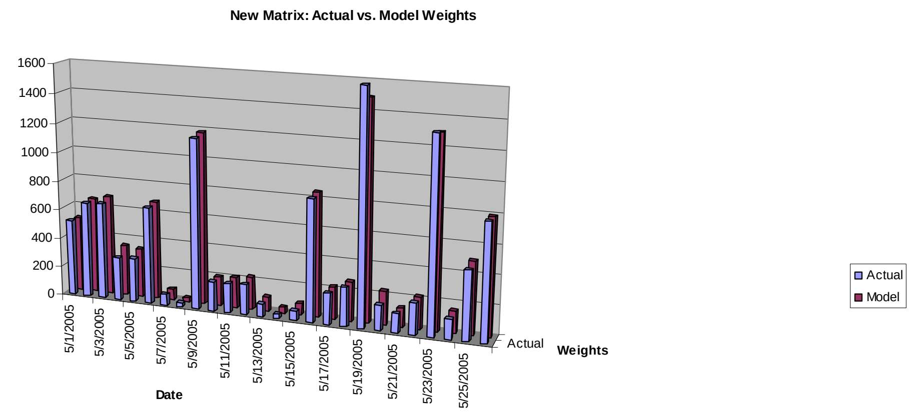


	1-May	2-May	3-May	4-May	5-May	6-May	7-May	8-May	9-May	10-May	11-May	12-May	13-May	14-May	15-May	16-May	17-May	18-May	19-May	20-May	21-May	22-May	23-May	24-May	25-May	26-May
Actual	8	9	8	10	9	6	4	1	8	3	5	5	3	2	3	9	5	5	5	5	5	8	8	7	7	4
Model	8	9	10	11	10	6	4	1	9	3	5	6	3	2	3	8	5	5	5	8	5	7	7	7	7	4

Figure 16. Model vs. Actual Schedule: Total Launch Facilities Scheduled

As the graph and table show, the model solutions and actual daily maintenance schedule outputs closely parallel one another. In six of the daily schedules, the research model scheduled more launch facilities than the actual baseline maintenance schedule. The actual schedule completed more launch facilities than the model in three daily schedules; however, in two of the three cases, the model's total weighted sum was greater than that of the actual schedule. Both the model solution and actual schedule completed the same number of launch facilities for the remaining 17 daily schedules. An average of the all 26 daily schedules suggests that the research model schedules one more launch facility than the actual maintenance schedule completed. As such, the research model appears to produce better solutions than the actual daily schedules.

A comparison of weighted sums for the model and actual maintenance schedule is shown in Figure 17.



	1-May	2-May	3-May	4-May	5-May	6-May	7-May	8-May	9-May	10-May	11-May	12-May	13-May	14-May	15-May	16-May	17-May	18-May	19-May	20-May	21-May	22-May	23-May	24-May	25-May	26-May
Actual	524	657	662	294	300	665	75	27	1165	200	202	208	88	32	66	836	215	268	1590	174	131	216	1325	137	473	797
Model	513	657	683	350	337	676	75	27	1181	200	208	223	99	43	82	847	220	268	1494	230	131	217	1304	154	495	797

Figure 17. Model vs. Actual Schedule: Weighted Sum Comparison

As with the numbered of scheduled launch facilities, the weighted sum outputs of the research model and actual maintenance schedules also closely coincide. However, the research model did outperform the actual schedule in 16 of the 26 daily schedules. In seven schedules, both produced identical weighted sums. The actual schedule did produce a higher weighted sum than the research model for the May 1, 19, and 23 schedules. Upon closer examination, it was observed that the launch facilities completed in these three actual maintenance schedules would require more than the two allotted security umbrellas. As such, they cannot be considered as the better of the two model solutions, given the constraints of two security umbrellas used to produce the model outputs. Again, the research model seems to outperform the actual schedule when comparing weighted sums.

In conclusion, using actual response time data greatly tightened the coverage area of each security umbrella, as compared to the geographical distance calculations used to develop the previous response time matrix. Even so, post analysis indicates that the research model still produces slightly better results than the actual maintenance schedule. All launch facilities scheduled by the research model fall within two, 60-minute security umbrellas, meeting the requirement currently mandated at F. E. Warren AFB. The research model could prove useful to schedulers if applied as part of every day scheduling practices.

Summary

This chapter reviewed the results obtained by comparing the research model solutions to the actual maintenance activities performed between May 1 and May 26, 2005 at F. E. Warren AFB, WY. Analysis results compare the weighted sum of launch facilities selected, number of open hole/penetrated launch facilities chosen for the daily schedule, and manpower utilization for both maintenance and security. Two sensitivity analysis models were performed: the first examined the effects of changing the security umbrella response times on weighted sums, number of launch facilities scheduled, and manpower utilization rates; the second set analyzed how changing the number of supportable security umbrellas, in conjunction with response times, affected the optimal daily schedule solutions. Post analysis was performed to consider the effects of using F. E. Warren AFB's actual security umbrella data on research model outputs. Chapter V includes discussion of this analysis and applicable conclusions derived from this analysis. Additionally, final recommendations and opportunities for future research will be offered.

V. Conclusions

Introduction

This chapter discusses pertinent conclusions that can be drawn from the results of model analysis. The conclusions and recommendations made from this research are only applicable to F. E. Warren AFB, but can be generalized to the remaining missile maintenance organizations by incorporating base-specific data into the final model. The conclusions are based strictly on the data analyzed and could change with a different set of data, assumptions, or variables. Future research opportunities are suggested that might improve the accuracy, validity, and usability of the research model. Computer screenshots of the research model can be observed in Appendices J-M.

Actual Schedule versus Model Solutions

As was observed in Chapter IV, the research model produced solutions for 8 of 26 daily schedules that were equivalent to the actual schedule solution. In 18 of the 26 daily schedules analyzed, the research model produced better weighted-sum solutions than were provided by the actual schedule. Improvements ranged from 2 percent to nearly 35 percent, with the number of daily scheduled launch facilities increasing between 0 and 3 additional launch facilities. The actual schedule had higher utilization rates for EMT, PMT, Pneudraulics, and Training teams, while the research model demonstrated higher utilization rates for the Corrosion, FMT, and Rivet Mile maintenance teams. In both models, the utilization rate for PMT was less than 50 percent, indicating an area for

further analysis. In addition to the primary model analysis, two sets of sensitivity analysis tests were performed using the research model.

The first sensitivity analysis monitored the effects of decreased security response times on the weighted sum of maintenance activities scheduled, number of launch facilities scheduled, and manpower utilization rates. As was expected, smaller security umbrellas resulted in a decrease in the final weighted-sum value of maintenance performed. The weighted sum decrease was less profound in the 30-minute through 60-minute security umbrella models, but more severe in the 20-minute model. The small weighted-sum differences observed between the 30- through 60-minute models is attributable to the large weights assigned to the high-priority maintenance categories. As security umbrella response times decreased, umbrella centers shifted to the missile alert facilities that covered those areas containing the high-priority maintenance activities. At each 10-minute decrement, maintenance activities with small weights, such as periodic maintenance and training, were gradually removed from the schedule. With the 20-minute security umbrella model, only the highest-priority launch facilities were selected.

The number of launch facilities selected by the research model was highly dependent on the random geographic clustering of required maintenance activities. Daily schedules that had more tightly clustered, higher-priority maintenance activities available, generally had more launch facilities selected by the model. As was observed with the weighted sums analysis, the weights assigned to maintenance categories greatly impacted the type and number of launch facilities scheduled. Reducing the weights assigned to the higher-priority maintenance activities could increase the total number of launch facilities scheduled, but at the expense of having several tightly-clustered, low-

priority maintenance activities bumping an important maintenance requirement, such as an off-alert launch facility, from the final schedule.

Personnel utilization rates generally decreased with smaller security umbrellas. Teams, such as Corrosion, CE, PMT, and Training, realized more than a 10-percent reduction in manpower utilization as security umbrella size decreased from 60 minutes to 40 minutes. High-priority teams, such as SETS, EMT, FMT, MHT, and MMT, realized less than a four percent change in utilization with these same reductions in response time. The 30-minute and 20-minute security umbrellas had a more severe impact on overall utilization rates, especially for periodic maintenance and training activities. This again is attributable to the weights assigned to the high-priority maintenance categories, as well as the geographic clustering of launch facility maintenance activities.

In the second round of sensitivity analysis, the number of available security umbrellas was adjusted between one and five. As with the first sensitivity analysis, response times were also adjusted between 20 and 60 minutes in 10-minute increments. It was found that as the number of available umbrellas increased, the best achieved weighted-sum solution could be realized with a shorter response time. Final results suggested that two, 60-minute security umbrellas were sufficient to maximize the weighted-sum solution for all 26 schedules, given current security and maintenance team availability. With 3 umbrellas, response time could be reduced to 50 minutes; with 4 umbrellas, response time could be reduced to 40 minutes; and with 5 umbrellas, response time could be reduced to 30 minutes. Additional umbrellas could be created if security forces personnel were to abandon their current deployment philosophy, which assigns more than one fire team per umbrella. Otherwise, if the current philosophy remains the

norm, major increases in security forces manpower would be required to create additional umbrellas.

Limitations

The research model relies on the ten assumptions outlined in Chapter IV. Each of these assumptions limits the model's ability to serve as a stand-alone scheduling tool. However, these limitations can be addressed in future research pertaining to the missile maintenance scheduling problem.

During sensitivity analysis of decreased security response times, it was discovered that the two, 60-minute security umbrellas developed from the model's straight-line response time matrix were more generous than the identical security umbrellas currently used by F. E. Warren AFB maintenance schedulers, which are based on actual response times. Figure 14 illustrated that the launch facilities chosen for the model solution set were, in reality, not all covered by F. E. Warren AFB's actual 60-minute security umbrellas. Four of the nine launch facilities fell outside the range of umbrella coverage. Assuming that the actual 60-minute security umbrellas constructed by F. E. Warren AFB are correct, this researcher had to conclude that the model output is not completely accurate because of real-world routing and driving times. This apparent shortcoming of the research model was provided within the model assumptions listed in Chapter IV: the response time matrix approximates actual response times.

Since the F. E. Warren AFB security umbrella coverage information was provided after all data analysis was completed, a post analysis of the model was performed. The original response time matrix, which was constructed using geographical distance

calculations, was substituted with actual launch facility coverage data provided for each of the 15 missile alert facilities. Although actual response times between the missile alert facilities and launch facilities were not available, the 60-minute security umbrella maps identified which launch facilities are covered by each missile alert facility. The absence of actual response times removed the research model's ability to adjust response time parameters, but allowed for a more accurate depiction of daily maintenance activities that can be completed.

Conclusions/Implications

Research analysis indicates that in all 26 cases, the two-stage heuristic model does provide solutions that are as good, or better, than actual schedules produced during May 1 through May 26, 2005 at F. E. Warren AFB. This research has demonstrated that current scheduling methods being used at F. E. Warren AFB can be enhanced through the use of optimization techniques. The time required to develop daily schedules can be reduced, while the energy invested in making schedule changes can be alleviated. By using optimization software, the experience level of maintenance schedulers may not have as much of an impact on the contents of daily schedules produced, as the model considers all possible maintenance activities that have the required maintenance teams, security personnel, parts, and equipment available for successful completion. The research model is able to select the two security umbrellas that best utilize all available maintenance teams and security personnel, given the resource and security constraints. From this set of missile alert facilities, the model is then able to produce feasible solutions that geographically cluster maintenance activities and maximize the weighted sum of

maintenance activities performed. In summary, the model produced in this research can be an effective tool for missile maintenance schedulers to supplement current scheduling processes.

Suggestions for Further Study

The research model developed in this thesis has great potential for success in the future of missile maintenance scheduling. The research problem dealt with multiple objectives: maximize the weighted sum of all maintenance activities at candidate launch facilities to establish the location of security umbrellas; then use this solution to choose the launch facilities within those security umbrella locations that again, maximize the weighted sum of maintenance activities. The model utilized a two-staged heuristic that employed discrete, linear and nonlinear optimization techniques to produce a solution. Future research could focus on developing a model that optimizes both objectives simultaneously, which would eliminate the need for two stages and could potentially produce better solutions.

There were ten assumptions and stipulations that limited the research model's functionality. The model only considered launch facility maintenance activities that required the presence of security escort teams (SETS) and/or other security forces personnel to be completed. Future research could focus on expanding these capabilities so that all missile maintenance activities are scheduled by the model. Additionally, the model assumed that each team could only work at one launch facility per day. Setting up the model so that it permits maintenance teams to visit multiple launch facilities can only improve the weighted sum of maintenance activities selected for the daily schedule.

Accomplishing both objectives would further simplify the missile maintenance scheduling process and pave the road for complete use of automation to produce daily missile maintenance schedules.

In the research model, security forces personnel were divided into two categories: SETS and other guards. However, more than two types of security teams actually exist, each with its own capabilities and constraints. Also, security personnel qualifications, such as team leader and team member status, greatly impact how security forces personnel can be utilized. The 790 MSFS currently utilizes a Microsoft Excel®-based guard calculator that differentiates between security teams and to some extent, considers the qualifications of their security personnel. Integrating this tool into the missile maintenance scheduling model could be the first step toward making the daily scheduling process a true joint effort between missile maintenance and missile security forces schedulers.

The Microsoft Excel® Premium Solver™ software was used to develop the research model in this thesis. There are literally dozens of optimization software solutions, such as Library of Efficient Data types and Algorithms (LEDA), Library of Location Algorithms (LOLA), Tcl/Tk, and LP-Solve, that could be used to develop a missile maintenance scheduling tool. Mathematical formulations and other information from this research can be used to build a more robust model within a different optimization program.

Dawson (2005) analyzed the effects of utilizing locations, in addition to the missile alert facilities, that could serve as the center for security umbrellas. Though the missile maintenance and security forces communities have not yet adopted this idea,

future research could integrate the model produced in this research and the Dawson (2005) model. This combined model could analyze the effects that using additional staging areas will have on the type and number of maintenance activities scheduled.

Summary

This chapter summarized the findings of this research. Model limitations were provided and suggestions for model improvement were presented. Conclusions and research implications were provided. Future research opportunities were offered in hopes of further demonstrating the improvements that can be offered by integrating more advanced quantitative methods into the missile maintenance scheduling process.

Appendix A: Missile Maintenance Priority Designators

ATTACHMENT 2

MISSILE MAINTENANCE PRIORITY DESIGNATORS

Table A2.1. Priority Designators.

MAINTENANCE PRIORITY	APPLICATION	SUGGESTED UND (Supply System Priority
1	Repair of critical equipment needed for safe operation of the weapon system Maintenance actions needed to prevent damage or further damage to the weapon system, avoid injury to personnel or render the weapon system safe	A

Appendix A: Missile Maintenance Priority Designators

2	Priority 2 maintenance is listed by order of relative priority Return of an LCC to operational status when three or more are non-operational in the same squadron Maintenance required to retain/return "A Category (CAT)" sorties to EWO alert status Actual EWO generation of "F CAT" and "L CAT" sorties Time change requirements for re-entry systems when the due date is within 30 days Maintenance required to reposture LFs and LCCs being returned from modification/test programs When a known environmental compliance discrepancy exists which could result in a violation of federal, state or local regulations or Air Force/base instructions Repair of severed, damaged or seriously degraded Hardened Intersite Cable System (HICS) Multiple outages of command and control systems (Strategic Automated Command and Control System (SACCS), Milstar, Air Force Satellite Communications (AFSATCOM), Survivable Low Frequency Communications System (SLFCS), ICBM SHF Satellite Terminal (ISST) and UHF Radio System) which will seriously jeopardize alert notification to two or more LCCs in a squadron Restoration of squadron IPD collection capability to the Missile Support Base Maintenance required to deposture LFs and LCCs committed to modification/command approved or directed test programs	A A

Appendix A: Missile Maintenance Priority Designators

33 (Cont)	Discrepancies expected to affect alert posture or degrade impact accuracy	A
	Discrepancies which are time sensitive as directed by technical data or which, because of the nature of the discrepancy, require periodic monitoring	
	Maintenance required to return an LCC to operational status when two are non-operational in the same squadron	
	Return of a single command and control communications system at an LCC involving SACCS, Milstar, AFSATCOM, SLFCS, EWO-2, Hardened Voice Channel (HVC), ISST or UHF Radio System	
	All PMC conditions not specifically identified as Priority 4	
	A hardness/survivability PMC discrepancy within the launch tube or which affects the missile	
	Maintenance to clear discrepancies which require camper alert teams	
	Support of Dash 6 periodic maintenance schedules even though the package may be composed of discrepancies of lower priority	A
	Support equipment requiring emergency repair or calibration, the lack of which will delay or prevent mission accomplishment	
	Critical end items and repairable spares designated "Priority Repair"	
	Actions to accomplish immediate MCLs	
	Maintenance required to bring serviceable quantities to established critical levels	

Appendix A: Missile Maintenance Priority Designators

4	Hardness/survivability discrepancies in the LERs, but not in the launch tube Outages on non-command and control communications systems Impairments to any command and control communications systems Scheduled training dispatches/tasks Training devices requiring repair which prevent or delay training Return of an LCC to operational status when four are operational in the same squadron	A
5	Hardness/survivability discrepancies in the LCC TCTOs and MCLs, which if not promptly completed, could exceed recession date; also MCLs designated as "Urgent" Overdue periodic inspections and overdue time change items Site or support equipment discrepancies not expected to result in a PMC condition, but if corrected will enhance safety, weapon system operation or reliability Impairments to non-command and control communication systems	B

Appendix A: Missile Maintenance Priority Designators

6	Periodic Inspections, TCTOs, MCLs and time change items Communications preventative maintenance inspections (PMI) Routine maintenance of training devices Scheduled calibration of support equipment not listed under a higher priority	B
7	Minor repair of missiles and support equipment not listed under a higher priority Fabrication and repair of weapon system items not carrying a higher priority of non-weapon system items Communication discrepancies which don't affect equipment status	C
8	Informational entries	N/A
9	Deferred discrepancies	N/A

Appendix B: Explanation for Ranking of 18 Maintenance Categories

1. *Limited Life Component/Reentry System (LLC/RS):* priority 2 maintenance activity; requires an enormous amount of coordination between many organizations, requires additional security that is not always available, and has considerable mission impact.

2. *Priority Maintenance Letter (PML) Off-Alert:* very similar to the *Off-Alert*, entailing the same type of maintenance tasks; considered a priority 2 maintenance activity, is critical to accomplishing the published objective, often requires additional security personnel, and entails a large amount of coordination; the *PML Off-Alert* is a special case of the *Off-Alert*, so is ranked as a higher category.

3. *Off-Alert:* very similar to the *PML Off-Alert*, entailing the same type of maintenance tasks; considered a priority 2 maintenance activity, is critical to accomplishing the published objective, often requires additional security personnel, and entails a large amount of coordination.

4. *Priority 1:* although the priority designator is higher than the previous three categories, these activities usually do not require the amount of coordination that the previous categories require, do not require as many security personnel, and usually have at least one team available daily to handle these situations as they arise.

5. *Concrete Headworks:* priority 8 designator; accomplishment of these programs are critical to achieve security requirements outlined in instruction DoD S-5210.41-M; will directly impact ability to accomplish missile maintenance activities in the near future. These maintenance activities did not appear to lose security force escorts when security manpower was short during May 1-26, 2005.

6. *Propulsion Replacement Program (PRP):* priority 2 designation; includes maintenance activities that do not fall into any previous category (i.e. downstage removal/installation); excludes "open hole" maintenance activities; requires fair amount of coordination, but not as many security personnel.

7. *Non-Mission Capable Missile Alert Facility (NMC MAF):* priority designation varies from 2 to 4, depending on the number of other MAFs available within the same squadron; security personnel may be required, depending on type of maintenance tasks required.

8. *Launch Facility Security Check Out (LF Security C/O):* priority 3 designation; requires additional security personnel to maintain LF control until discrepancy is eliminated; can impact the number of security force personnel available to maintenance teams in successive daily schedules.

9. *Time Sensitive (TS) Priority 3:* listed as second most important priority 3 maintenance activity in AFSPCI 21-114; security escort requirements can vary, depending on level of LF access required.

Appendix B: Explanation for 18 Maintenance Category Ranking

10. *Corrosion Control (CCT):* priority designation ranges from 3 to 8, depending on extent of periodic maintenance activities required; assigned same weight as PMT and RVM, as all are considered periodic maintenance activities; number of security personnel required is dependent on level of LF access and presence of critical components.

11. *Periodic Maintenance Team (PMT):* priority designation ranges from 3 to 8, depending on extent of periodic maintenance activities required; assigned same weight as CCT and RVM, as all are considered periodic maintenance activities; number of security personnel required is dependent on level of LF access and presence of critical components.

12. *Rivet Mile (RVM):* priority designation ranges from 3 to 8, depending on extent of periodic maintenance activities required; assigned same weight as CCT and PMT, as all are considered periodic maintenance activities; number of security personnel required is dependent on level of LF access and presence of critical components.

13. *PRP Open Hole:* priority designation ranges from 3 to 8, depending on extent of periodic maintenance activities required; number of security personnel required varies on level of LF access and presence of critical components; requires coordination with several organizations to begin; limited time frame for completion without further coordination.

14. *Priority 2-3:* includes all maintenance activities that don't fall into previous categories; may require presence of security personnel, depending on level of LF access; may not be practical to complete if maintenance requires penetration due to limited number of security personnel available.

15. *Batteries:* priority 3 designator; requires fair amount of coordination, but does not occur regularly; utilizes special Electro-Mechanical Team (EMT) to complete; always requires security force presence.

16. *Training:* priority 4 designator; can be used to complete mission essential tasks which would fall into a higher category; training usually one of the first teams to lose security escorts when higher mission requirements dictate.

17. *Priority 4-7:* maintenance tasks that do not fall into previous categories; usually not practical to complete alone when security presence is required; often completed in conjunction with higher priority maintenance activities; minimal impact to published objective.

18. *Miscellaneous Missile Alert Facility (Misc. MAF):* low-priority tasks that generally do not require presence of security personnel; any tasks at a MAF not falling within a higher category; generally have little to no direct impact on the published objective.

Appendix C: Comparison of Four Solver Algorithm Outputs

Date	Decision Variable Settings		Standard Evolutionary Search Algorithms						Standard GRG Nonlinear	
			Random Localized		Deterministic		Nonlinear Gradient			
	Stage 1	Stage 2	Weighted Sum	# of Sites	Weighted Sum	# of Sites	Weighted Sum	# of Sites	Weighted Sum	# of Sites
1-May-05	0	0	302	9	302	9	302	9	302	9
	1	1	302	9	302	9	302	9	302	9
	0	1	302	9	302	9	302	9	302	9
	1	0	302	9	302	9	302	9	302	9
2-May-05	0	0	475	10	475	10	475	10	465	10
	1	1	475	10	475	10	475	10	465	10
	0	1	475	10	475	10	475	10	465	10
	1	0	475	10	475	10	475	10	465	10
3-May-05	0	0	555	10	555	10	555	10	555	10
	1	1	555	10	555	10	555	10	555	10
	0	1	555	10	555	10	555	10	555	10
	1	0	555	10	555	10	555	10	555	10
4-May-05	0	0	407	12	407	12	407	12	407	12
	1	1	407	12	407	12	407	12	407	12
	0	1	407	12	407	12	407	12	407	12
	1	0	407	12	407	12	407	12	407	12
5-May-05	0	0	404	12	383	11	404	12	383	11
	1	1	404	12	383	11	404	12	383	11
	0	1	404	12	383	11	404	12	383	11
	1	0	404	12	383	11	404	12	383	11
6-May-05	0	0	280	5	280	5	280	5	280	5
	1	1	280	5	280	5	280	5	280	5
	0	1	280	5	280	5	280	5	280	5
	1	0	280	5	280	5	280	5	280	5
7-May-05	0	0	75	4	75	4	75	4	75	4
	1	1	75	4	75	4	75	4	75	4
	0	1	75	4	75	4	75	4	75	4
	1	0	75	4	75	4	75	4	75	4
8-May-05	0	0	27	1	27	1	27	1	27	1
	1	1	16	1	27	1	27	1	27	1
	0	1	27	1	27	1	27	1	27	1
	1	0	16	1	27	1	27	1	27	1
9-May-05	0	0	604	9	604	9	604	9	604	9
	1	1	604	9	604	9	604	9	604	9
	0	1	604	9	604	9	604	9	604	9
	1	0	604	9	604	9	604	9	604	9

Appendix C: Comparison of Four Solver Algorithm Outputs

Date	Decision Variable Settings		Standard Evolutionary Search Algorithms						Standard GRG Nonlinear	
			Random Localized		Deterministic		Nonlinear Gradient			
	Stage 1	Stage 2	Weighted Sum	# of Sites	Weighted Sum	# of Sites	Weighted Sum	# of Sites	Weighted Sum	# of Sites
10-May-05	0	0	261	4	261	4	261	4	261	4
	1	1	261	4	261	4	261	4	261	4
	0	1	261	4	261	4	261	4	261	4
	1	0	261	4	261	4	261	4	261	4
11-May-05	0	0	253	6	253	6	264	6	264	6
	1	1	264	6	253	6	253	6	264	6
	0	1	253	6	253	6	264	6	264	6
	1	0	264	6	253	6	253	6	264	6
12-May-05	0	0	274	6	269	6	274	6	269	6
	1	1	274	6	263	6	269	6	269	6
	0	1	274	6	269	6	274	6	269	6
	1	0	274	6	263	6	269	6	269	6
13-May-05	0	0	99	3	88	3	99	3	99	3
	1	1	99	3	99	3	99	3	99	3
	0	1	99	3	88	3	99	3	99	3
	1	0	99	3	99	3	99	3	99	3
14-May-05	0	0	59	3	59	3	59	3	59	3
	1	1	48	3	48	3	59	3	59	3
	0	1	59	3	59	3	59	3	59	3
	1	0	48	3	48	3	59	3	59	3
15-May-05	0	0	71	3	82	3	82	3	82	3
	1	1	82	3	71	3	82	3	82	3
	0	1	71	3	82	3	82	3	82	3
	1	0	82	3	71	3	82	3	82	3
16-May-05	0	0	547	10	531	9	547	10	547	10
	1	1	531	9	547	10	547	10	547	10
	0	1	547	10	531	9	547	10	547	10
	1	0	531	9	547	10	547	10	547	10
17-May-05	0	0	288	5	288	5	288	5	288	5
	1	1	288	5	288	5	288	5	288	5
	0	1	288	5	288	5	288	5	288	5
	1	0	288	5	288	5	288	5	288	5
18-May-05	0	0	308	5	308	5	308	5	308	5
	1	1	308	5	308	5	308	5	308	5
	0	1	308	5	308	5	308	5	308	5
	1	0	308	5	308	5	308	5	308	5
19-May-05	0	0	646	5	646	5	646	5	646	5
	1	1	646	5	646	5	646	5	646	5
	0	1	646	5	646	5	646	5	646	5
	1	0	646	5	646	5	646	5	646	5
20-May-05	0	0	220	7	220	7	220	7	220	7
	1	1	220	7	220	7	220	7	220	7
	0	1	220	7	220	7	220	7	220	7
	1	0	220	7	220	7	220	7	220	7
21-May-05	0	0	131	5	131	5	131	5	131	5
	1	1	131	5	131	5	131	5	131	5
	0	1	131	5	131	5	131	5	131	5
	1	0	131	5	131	5	131	5	131	5
22-May-05	0	0	238	8	238	8	217	7	238	8
	1	1	238	8	238	8	238	8	238	8
	0	1	238	8	238	8	217	7	238	8
	1	0	238	8	238	8	238	8	238	8
23-May-05	0	0	545	8	534	8	534	8	545	8
	1	1	545	8	545	8	540	8	545	8
	0	1	545	8	534	8	534	8	545	8
	1	0	545	8	545	8	540	8	545	8
24-May-05	0	0	165	7	165	7	165	7	165	7
	1	1	165	7	154	7	154	7	165	7
	0	1	165	7	165	7	165	7	165	7
	1	0	165	7	154	7	154	7	165	7
25-May-05	0	0	257	7	257	7	247	6	257	7
	1	1	247	6	247	6	220	5	257	7
	0	1	257	7	257	7	247	6	257	7
	1	0	247	6	247	6	220	5	257	7
26-May-05	0	0	321	4	321	4	321	4	321	4
	1	1	321	4	321	4	321	4	321	4
	0	1	321	4	321	4	321	4	321	4
	1	0	321	4	321	4	321	4	321	4

Appendix D: Repeatability Results of Standard GRG Nonlinear Method

Date	Standard GRG Nonlinear (1st Run)		Standard GRG Nonlinear (2nd Run)		Standard GRG Nonlinear (3rd Run)	
	Final Weighted Total	# of Sites	Final Weighted Total	# of Sites	Final Weighted Total	# of Sites
1-May-05	302	9	302	9	302	9
	302	9	302	9	302	9
	302	9	302	9	302	9
	302	9	302	9	302	9
2-May-05	465	10	475	10	475	10
	465	10	475	10	475	10
	465	10	475	10	475	10
	465	10	475	10	475	10
3-May-05	555	10	555	10	555	10
	555	10	555	10	555	10
	555	10	555	10	555	10
	555	10	555	10	555	10
4-May-05	407	12	407	12	407	12
	407	12	407	12	407	12
	407	12	407	12	407	12
	407	12	407	12	407	12
5-May-05	383	11	404	11	404	11
	383	11	404	11	404	11
	383	11	404	11	404	11
	383	11	404	11	404	11
6-May-05	280	5	280	5	280	5
	280	5	280	5	280	5
	280	5	280	5	280	5
	280	5	280	5	280	5
7-May-05	75	4	75	4	75	4
	75	4	75	4	75	4
	75	4	75	4	75	4
	75	4	75	4	75	4
8-May-05	27	1	27	1	27	1
	27	1	27	1	27	1
	27	1	27	1	27	1
	27	1	27	1	27	1
9-May-05	604	9	604	9	604	9
	604	9	604	9	604	9
	604	9	604	9	604	9
	604	9	604	9	604	9
10-May-05	261	4	261	4	261	4
	261	4	261	4	261	4
	261	4	261	4	261	4
	261	4	261	4	261	4
11-May-05	264	6	264	6	264	6
	264	6	264	6	264	6
	264	6	264	6	264	6
	264	6	264	6	264	6
12-May-05	269	6	274	6	274	6
	269	6	274	6	274	6
	269	6	274	6	274	6
	269	6	274	6	274	6
13-May-05	99	3	99	3	99	3
	99	3	99	3	99	3
	99	3	99	3	99	3
	99	3	99	3	99	3

Appendix D: Repeatability Results of Standard GRG Nonlinear Method

Date	Standard GRG Nonlinear (1st Run)		Standard GRG Nonlinear (2nd Run)		Standard GRG Nonlinear (3rd Run)	
	Final Weighted Total	# of Sites	Final Weighted Total	# of Sites	Final Weighted Total	# of Sites
14-May-05	59	3	59	3	59	3
	59	3	59	3	59	3
	59	3	59	3	59	3
	59	3	59	3	59	3
15-May-05	82	3	82	3	82	3
	82	3	82	3	82	3
	82	3	82	3	82	3
	82	3	82	3	82	3
16-May-05	547	10	547	10	547	10
	547	10	547	10	547	10
	547	10	547	10	547	10
	547	10	547	10	547	10
17-May-05	288	5	288	5	288	5
	288	5	288	5	288	5
	288	5	288	5	288	5
	288	5	288	5	288	5
18-May-05	308	5	308	5	308	5
	308	5	308	5	308	5
	308	5	308	5	308	5
	308	5	308	5	308	5
19-May-05	646	5	646	5	646	5
	646	5	646	5	646	5
	646	5	646	5	646	5
	646	5	646	5	646	5
20-May-05	220	7	220	7	220	7
	220	7	220	7	220	7
	220	7	220	7	220	7
	220	7	220	7	220	7
21-May-05	131	5	131	5	131	5
	131	5	131	5	131	5
	131	5	131	5	131	5
	131	5	131	5	131	5
22-May-05	238	8	238	8	238	8
	238	8	238	8	238	8
	238	8	238	8	238	8
	238	8	238	8	238	8
23-May-05	545	8	545	8	545	8
	545	8	545	8	545	8
	545	8	545	8	545	8
	545	8	545	8	545	8
24-May-05	165	7	165	7	165	7
	165	7	165	7	165	7
	165	7	165	7	165	7
	165	7	165	7	165	7
25-May-05	257	7	257	7	257	7
	257	7	257	7	257	7
	257	7	257	7	257	7
	257	7	257	7	257	7
26-May-05	321	4	321	4	321	4
	321	4	321	4	321	4
	321	4	321	4	321	4
	321	4	321	4	321	4

Appendix E: Actual Schedule vs. Model Solution Comparison

May	Time		Weight	LFs	MAF	SETS	Other	BATT	CCT	CE	EMT	FMT	MHT	MMT	PMT	PNEU	RVM	TRN	Stby/PK
1	60	**Actual**	524	8		14/22	15/15	0/0	1/1	0/0	2/2	2/3	0/0	2/2	0/0	1/1	2/2	0/0	
		Model	540	9	F,L	16/22	15/15	0/0	1/1	0/0	2/2	3/3	0/0	2/2	0/0	1/1	2/2	0/0	
2	60	**Actual**	657	9		15/18	15/15	0/0	2/2	2/2	2/3	1/3	0/0	4/4	0/0	0/0	2/2	0/0	
		Model	673	10	F,O	17/18	15/15	0/0	2/2	2/2	2/3	2/3	0/0	4/4	0/0	0/0	2/2	0/0	
3	60	**Actual**	662	8		17/17	0/22	0/0	0/2	2/2	1/3	0/2	1/1	2/2	3/3	0/0	2/3	1/2	
		Model	753	10	E,G	17/17	15/22	0/0	2/2	2/2	1/3	0/2	1/1	2/2	2/3	0/0	2/3	1/2	
4	60	**Actual**	294	10		19/28	0/0	1/1	1/1	2/2	0/3	1/2	1/1	1/1	3/3	1/1	1/1	0/0	1 Stby
		Model	367	12	E,G	21/28	0/0	1/1	1/1	2/2	0/3	2/2	1/1	1/1	3/3	0/1	1/1	0/0	
5	60	**Actual**	300	9		15/19	0/0	0/0	1/1	2/2	1/2	0/2	1/1	1/1	2/3	0/0	1/2	1/2	2 Stby, 1 PK
		Model	358	11	E,G	18/19	0/0	0/0	1/1	2/2	0/2	2/2	1/1	1/1	2/3	0/0	2/2	1/2	
6	60	**Actual**	665	6		12/12	22/22	0/0	0/0	0/0	4/6	2/2	0/0	2/4	1/1	0/1	0/0	1/1	1 PK
		Model	686	6	E,F	12/12	22/22	0/0	0/0	0/0	2/6	2/2	0/0	4/4	1/1	0/1	0/0	1/1	
7	60	**Actual**	75	4		8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	
		Model	75	4	E,F	8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	
8	60	**Actual**	27	1		2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0	0/0	0/0	0/0	0/0	2 Stby
		Model	27	1	E,F	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0	0/0	0/0	0/0	0/0	
9	60	**Actual**	1165	8		15/15	37/37	0/0	1/1	2/2	2/3	1/2	0/0	4/5	0/0	0/0	2/2	0/0	2 PK
		Model	1192	9	E,G	15/15	37/37	0/0	1/1	2/2	2/3	2/2	0/0	4/5	0/0	0/0	2/2	0/0	
10	60	**Actual**	200	3		5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1	0/1	0/0	0/1	0/0	1 Stby
		Model	200	3	E,G	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1	0/1	0/0	0/1	0/0	
11	60	**Actual**	202	5		9/9	0/0	0/0	0/0	2/2	1/2	0/2	0/0	0/2	0/0	0/0	2/2	0/0	1 Stby
		Model	213	5	E,G	9/9	0/0	0/0	0/0	2/2	0/2	1/2	0/0	0/2	0/0	0/0	2/2	0/0	
12	60	**Actual**	208	5		10/10	0/0	0/0	0/1	2/2	0/3	2/2	0/0	0/2	0/0	0/0	2/2	0/0	1 Stby, 1 PK
		Model	234	6	E,G	10/10	0/0	0/0	1/1	2/2	0/3	1/2	0/0	0/2	0/0	0/0	2/2	0/0	
13	60	**Actual**	88	3		5/5	0/0	0/0	0/0	0/0	1/2	0/2	1/1	1/2	0/0	1/1	0/0	0/0	1 Stby
		Model	99	3	F,L	5/5	0/0	0/0	0/0	0/0	1/2	1/2	1/1	2/2	0/0	0/1	0/0	0/0	
14	60	**Actual**	32	2		4/4	0/0	0/0	0/0	0/0	0/2	0/2	0/0	0/0	0/0	0/0	0/0	0/0	1 Stby
		Model	43	2	E,F	4/4	0/0	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	0/0	0/0	
15	60	**Actual**	66	3		5/5	4/4	0/0	0/0	0/0	2/2	1/2	0/0	0/0	0/0	0/0	0/1	0/0	1 Stby
		Model	82	3	E,G	5/5	4/4	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	1/1	0/0	
16	60	**Actual**	836	9		13/14	24/26	0/0	1/1	2/2	3/3	0/2	0/0	2/2	2/2	0/0	1/2	1/1	1 Stby, 1 PK
		Model	853	8	D,J	14/14	26/26	0/0	1/1	2/2	2/3	1/2	0/0	2/2	1/2	0/0	2/2	0/1	
17	60	**Actual**	215	5		8/8	2/2	0/0	0/1	2/2	2/2	0/2	0/0	0/4	0/3	0/0	1/2	0/1	
		Model	226	5	E,G	8/8	2/2	0/0	0/1	2/2	2/2	0/2	0/0	0/4	0/3	0/0	1/2	0/1	
18	60	**Actual**	268	5		6/6	6/6	0/0	0/1	2/2	2/2	0/2	1/1	2/4	0/2	0/0	0/0	0/1	
		Model	268	5	E,F	6/6	6/6	0/0	0/1	2/2	2/2	0/2	1/1	2/4	0/2	0/0	0/0	0/1	
19	60	**Actual**	1590	5		10/10	44/44	0/0	0/2	2/2	1/1	1/2	0/0	4/4	0/1	0/0	0/3	0/0	
		Model	1590	5	E,G	10/10	44/44	0/0	0/2	2/2	1/1	1/2	0/0	4/4	0/1	0/0	0/3	0/0	
20	60	**Actual**	174	5		6/10	23/23	0/0	0/0	0/0	3/4	1/2	0/0	4/4	0/0	0/0	0/3	0/1	2 Stby
		Model	230	8	I,J	10/10	23/23	0/0	0/0	0/0	2/4	2/2	0/0	4/4	0/0	0/0	2/3	1/1	
21	60	**Actual**	131	5		9/10	2/2	0/0	0/0	0/0	2/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	1 Stby (1 cop)
		Model	131	5	E,G	9/10	2/2	0/0	0/0	0/0	2/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	
22	60	**Actual**	216	8		15/16	0/0	0/0	1/1	0/0	2/2	2/2	0/0	0/0	0/0	0/0	3/3	0/0	1 Stby (1 cop)
		Model	238	8	E,G	15/16	0/0	0/0	1/1	0/0	2/2	2/2	0/0	0/0	0/0	0/0	3/3	0/0	
23	60	**Actual**	1325	8		14/14	37/37	0/0	1/1	0/0	3/3	2/2	0/0	4/4	0/1	0/0	3/3	0/0	
		Model	1325	8	E,G	14/14	37/37	0/0	1/1	0/0	3/3	2/2	0/0	4/4	0/1	0/0	3/3	0/0	
24	60	**Actual**	137	7		12/12	0/0	0/0	1/2	0/0	0/1	1/3	0/0	0/0	0/0	0/0	4/4	0/0	
		Model	165	7	E,G	12/12	0/0	0/0	1/2	0/0	0/1	3/3	0/0	0/0	0/0	0/0	4/4	0/0	
25	60	**Actual**	473	7		12/14	0/0	0/0	1/1	0/0	1/1	2/2	0/0	4/4	0/0	0/0	2/2	1/1	1 Stby
		Model	495	7	E,J	14/14	0/0	0/0	1/1	0/0	1/1	2/2	0/0	4/4	0/0	0/0	1/2	1/1	
26	60	**Actual**	797	4		7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4	0/0	0/0	0/1	0/0	
		Model	797	4	J,L	7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4	0/0	0/0	0/1	0/0	

Appendix E: Actual Schedule vs. Model Solution Comparison

May	Time		LFs
1	60	**Actual**	B04,C03,C05,C06,G07,H02,H08,N03,
		Model	B04,C03,C05,C06,E04,G07,H02,L08,N03
2	60	**Actual**	A09,C03,C05,E03,G07,H08,M09,N03,N04
		Model	A09,C03,C05,E03,G07,H08,L08,M09,N03,N04
3	60	**Actual**	B05,C05,E04,F02,H10,I03,N03,N04
		Model	B05,C03,C05,E03,E04,F02,G07,H08,N03,N04
4	60	**Actual**	C03,C05,C06,E03,F04,G07,G11,I03,N03,N04
		Model	B08,C03,C05,E03,F04,G07,G11,H08,I02,M09,N03,N04
5	60	**Actual**	A11,B08,C04,C08,G07,I03,M09,M03,N04
		Model	A11,C04,C08,F10,G07,H08,I02,I03,M09,N03,N04
6	60	**Actual**	B04,B10,C05,C11,F04,H09
		Model	A06,B04,C05,C11,F04,I02
7	60	**Actual**	B04,F07,I02,M09
		Model	B04,F07,F10,I02
8	60	**Actual**	B04
		Model	B04
9	60	**Actual**	A04,E04,F10,I03,J04,M09,N05,N06
		Model	B04,E04,F10,G07,H08,J04,M09,N05,N06
10	60	**Actual**	H08,N05,N06
		Model	H08,N05,N06
11	60	**Actual**	H04,I03,M09,N05,N06
		Model	B04,I03,M09,N05,N06
12	60	**Actual**	B04,I03,J09,N05,N06
		Model	B04,G07,I03,M09,N05,N06
13	60	**Actual**	B10,E08,G07
		Model	B04,B10,G07
14	60	**Actual**	F08,J11
		Model	B04,E04
15	60	**Actual**	E04,J02,J11
		Model	B04,I03,J02
16	60	**Actual**	A11,F05,F07,G07,J02,J09,M09,N02,N11
		Model	B04,F05,I03,J02,J09,M09,N02,N11
17	60	**Actual**	H02,J07,K07,N02,N11
		Model	B04,J09,M09,,N02,N11
18	60	**Actual**	C10,J02,J09,N02,N11
		Model	C10,H02,J09,N02,N11
19	60	**Actual**	B04,H05,H08,N02,N11
		Model	B04,H05,H08,N02,N11
20	60	**Actual**	C10,G07,H02,J06,J07
		Model	A11,B04,F05,G07,H02,I03,J07,J09
21	60	**Actual**	A09,B04,C04,C10,E04
		Model	A09,B04,C04,C10,E04
22	60	**Actual**	G07,H09,I03,I04,J09,K04,K07,M09
		Model	A09,B04,G07,I03,I04,J09,K07,M09
23	60	**Actual**	B04,G05,G07,I03,I04,J09,K07,M09
		Model	B04,G05,G07,I03,I04,J09,K07,M09
24	60	**Actual**	A09,E04,I03,J09,K02,K07,M09
		Model	A09,C07,I03,J08,J09,K07,M09
25	60	**Actual**	C07,I03,J09,K07,K11,M09
		Model	A06,A11,C07,J08,J09,K07,K11
26	60	**Actual**	J08,K09,L04,M09
		Model	J08,K09,L04,M09

Appendix F: Actual Schedule vs. Model Solution Sensitivity Analysis

May	Time	Weight	LFs	MAF	SETS	Other	BATT	CCT	CE	EMT	FMT	MHT	MMT	PMT	PNEU	RVM	TRN	LFs
1	60	540	9	F,L	16/22	15/15	0/0	1/1	0/0	2/2	3/3	0/0	2/2	0/0	1/1	2/2	0/0	B04,C03,C05,C06,E04,G07,H02,L08,N03
	50	506	8	D,J	14/22	15/15	0/0	1/1	0/0	1/2	3/3	0/0	2/2	0/0	1/1	2/2	0/0	B04,C03,C05,C06,E04,G07,L08,N03
	40	497	7	D,G	12/22	15/15	0/0	1/1	0/0	2/2	1/3	0/0	2/2	0/0	1/1	2/2	0/0	B04,C03,C05,C06,E04,G07,H02
	30	497	7	C,H	12/22	15/15	0/0	1/1	0/0	2/2	1/3	0/0	2/2	0/0	1/1	2/2	0/0	B04,C03,C05,C06,G07,H02,H08
	20	460	5	C,H	9/22	15/15	0/0	0/1	0/0	2/2	1/3	0/0	2/2	0/0	0/1	2/2	0/0	B04,C03,C05,H02,H08
2	60	673	10	F,O	17/18	15/15	0/0	2/2	2/2	2/3	2/3	0/0	4/4	0/0	0/0	2/2	0/0	A09,C03,C05,E03,G07,H08,L08,M09,N03,N04
	50	657	9	F,N	15/18	15/15	0/0	2/2	2/2	2/3	1/3	0/0	4/4	0/0	0/0	2/2	0/0	C03,C05,E03,G07,H08,L08,M09,N03,N04
	40	621	8	D,L	15/18	15/15	0/0	1/2	2/2	3/3	1/3	0/0	4/4	0/0	0/0	1/2	0/0	B08,C03,C05,E03,L08,M09,N03,N04
	30	615	7	C,L	13/18	15/15	0/0	1/2	2/2	2/3	1/3	0/0	4/4	0/0	0/0	1/2	0/0	C03,C05,E03,L08,M09,N03,N04
	20	578	5	C,M	9/18	15/15	0/0	0/2	2/2	2/3	0/3	0/0	4/4	0/0	0/0	1/2	0/0	C03,C05,M09,N03,N04
3	60	753	10	E,G	17/17	15/22	0/0	2/2	2/2	1/3	0/2	1/1	2/2	2/3	0/0	2/3	1/2	B05,C03,C05,E03,E04,F02,G07,H08,N03,N04
	50	753	10	F,N	17/17	15/22	0/0	2/2	2/2	1/3	0/2	1/1	2/2	2/3	0/0	2/3	1/2	B05,C03,C05,E03,E04,F02,G07,H08,N03,N04
	40	651	10	D,G	17/17	15/22	0/0	2/2	0/2	1/3	0/2	1/1	2/2	3/3	0/0	3/3	1/2	B05,C03,C05,E03,E04,F02,F04,G07,H08,I03
	30	553	7	C,H	12/17	15/22	0/0	1/2	0/2	1/3	0/2	0/1	2/2	2/3	0/0	3/3	1/2	B05,C03,C05,F02,G07,H08,I03
	20	434	3	C,H	5/17	15/22	0/0	0/2	0/2	1/3	0/2	0/1	2/2	0/3	0/0	2/3	0/2	C03,C05,H08
4	60	367	12	E,G	21/28	0/0	1/1	1/1	2/2	0/3	2/2	1/1	1/1	3/3	0/1	1/1	0/0	B08,C03,C05,E03,F04,G07,G11,H08,I02,M09,N
	50	340	10	G,O	17/28	0/0	1/1	1/1	2/2	0/3	2/2	1/1	1/1	2/3	0/1	1/1	0/0	C05,E03,F04,G07,G11,H08,I02,M09,N03,N04
	40	319	9	G,L	15/28	0/0	1/1	1/1	2/2	0/3	2/2	1/1	1/1	1/3	0/1	1/1	0/0	E03,F04,G07,G11,H08,I02,M09,N03,N04
	30	298	8	H,L	13/28	0/0	1/1	1/1	2/2	0/3	2/2	1/1	1/1	0/3	0/1	1/1	0/0	E03,F04,G07,G11,H08,I02,M09,N03,N04
	20	276	7	G,M	11/28	0/0	1/1	1/1	2/2	0/3	0/2	1/1	1/1	1/3	0/1	1/1	0/0	F04,G07,G11,H08,M09,N03,N04
5	60	358	11	E,G	18/19	0/0	0/0	1/1	2/2	0/2	2/2	1/1	1/1	2/3	0/0	2/2	1/2	A11,C04,C08,F10,G07,H08,I02,I03,M09,N03,N
	50	306	8	J,O	13/19	0/0	0/0	1/1	2/2	0/2	2/2	1/1	1/1	0/3	0/0	2/2	0/2	F10,G07,H08,I02,I03,M09,N03,N04
	40	306	8	I,L	13/19	0/0	0/0	1/1	2/2	0/2	2/2	1/1	1/1	0/3	0/0	2/2	0/2	G07,H08,I02,I03,L08,M09,N03,N04
	30	306	8	I,L	13/19	0/0	0/0	1/1	2/2	0/2	2/2	1/1	1/1	0/3	0/0	2/2	0/2	G07,H08,I02,I03,L08,M09,N03,N04
	20	269	6	I,M	10/19	0/0	0/0	1/1	2/2	0/2	1/2	1/1	1/1	0/3	0/0	1/2	0/2	G07,I02,I03,L08,M09,N03,N04
6	60	686	6	E,F	12/12	22/22	0/0	0/0	0/0	2/6	2/2	0/0	4/4	1/1	0/1	0/0	1/1	A06,B04,C05,C11,F04,I02
	50	686	6	D,J	12/12	22/22	0/0	0/0	0/0	2/6	2/2	0/0	4/4	1/1	0/1	0/0	1/1	A06,B04,C05,C11,F04,I02
	40	686	6	D,G	12/12	22/22	0/0	0/0	0/0	2/6	2/2	0/0	4/4	1/1	0/1	0/0	1/1	A06,B04,C05,C11,F04,I02
	30	670	5	D,G	10/12	22/22	0/0	0/0	0/0	2/6	2/2	0/0	2/4	1/1	0/1	0/0	1/1	B04,C05,C11,F04,I02
	20	622	3	C,E	6/12	22/22	0/0	0/0	0/0	2/6	1/2	0/0	2/4	0/1	0/1	0/0	1/1	B04,C05,C11
7	60	75	4	E,F	8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	B04,F07,F10,I02
	50	75	4	E,G	8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	B04,F07,F10,I02
	40	75	4	B,J	8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	B04,F07,F10,I02
	30	75	4	C,G	8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	B04,F07,F10,I02
	20	43	2	I,L	4/10	0/0	0/0	0/0	0/0	0/2	2/3	0/0	0/0	0/0	0/0	0/0	0/0	I02,L08
8	60	27	1	E,F	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0	0/0	0/0	0/0	0/0	B04
	50	27	1	E,F	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0	0/0	0/0	0/0	0/0	B04
	40	27	1	D,E	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0	0/0	0/0	0/0	0/0	B04
	30	27	1	D,L	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0	0/0	0/0	0/0	0/0	B04
	20	27	1	B,F	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0	0/0	0/0	0/0	0/0	B04
9	60	1192	9	E,G	15/15	37/37	0/0	1/1	2/2	2/3	2/2	0/1	4/5	0/0	0/0	2/2	0/0	B04,E04,F10,G07,H08,J04,M09,N05,N06
	50	1181	9	J,O	15/15	37/37	0/0	1/1	2/2	2/3	2/2	0/1	4/5	0/0	0/0	2/2	0/0	E04,F10,G07,H08,J04,L08,M09,N05,N06
	40	1171	8	D,M	15/15	37/37	0/0	1/1	2/2	2/3	2/2	0/1	4/5	0/0	0/0	1/2	0/0	A04,B04,E04,F10,J04,M09,N05,N06
	30	1021	6	I,L	10/15	37/37	0/0	1/1	0/2	2/3	1/2	0/1	4/5	0/0	0/0	2/2	0/0	E04,G07,H08,I03,J04,L08
	20	942	2	E,J	4/15	37/37	0/0	0/1	0/2	2/3	0/2	0/1	4/5	0/0	0/0	0/2	0/0	E04,J04
10	60	200	3	E,G	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1	0/1	0/1	0/1	0/2	H08,N05,N06
	50	200	3	F,O	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1	0/1	0/1	0/1	0/2	H08,N05,N06
	40	200	3	J,L	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1	0/1	0/1	0/1	0/2	H08,N05,N06
	30	200	3	H,N	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1	0/1	0/1	0/1	0/2	H08,N05,N06
	20	200	3	G,N	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1	0/1	0/1	0/1	0/2	H08,N05,N06
11	60	213	5	E,G	11/11	0/0	0/0	0/0	2/2	1/2	2/2	0/0	0/2	0/0	0/0	1/1	0/2	B04,I03,M09,N05,N06
	50	202	5	G,O	11/11	0/0	0/0	0/0	2/2	2/2	0/2	0/0	2/2	0/0	0/0	1/1	0/2	A06,I03,M09,N05,N06
	40	208	5	D,L	11/11	0/0	0/0	0/0	2/2	1/2	2/2	0/0	0/2	0/0	0/0	1/1	0/2	A06,B04,M09,N05,N06
	30	208	5	D,N	11/11	0/0	0/0	0/0	2/2	1/2	2/2	0/0	0/2	0/0	0/0	1/1	0/2	B04,E04,M09,N05,N06
	20	171	3	C,N	6/11	0/0	0/0	0/0	2/2	0/2	1/2	0/0	0/2	0/0	0/0	0/1	0/2	B04,N05,N06

Appendix F: Actual Schedule vs. Model Solution Sensitivity Analysis

May	Time	Weight	LFs	MAF	SETS	Other	BATT	CCT	CE	EMT	FMT	MHT	MMT	PMT	PNEU	RVM	TRN	LFs
12	60	234	6	E,G	10/10	0/0	0/0	1/1	2/2	0/3	1/2	0/2	0/2	0/0	0/0	2/2	0/2	B04,G07,I03,M09,N05,N06
	50	218	6	D,L	10/10	0/0	0/0	0/1	2/2	0/3	1/2	0/2	2/2	0/0	0/0	1/2	1/2	A06,A11,B04,M09,N05,N06
	40	218	6	D,L	10/10	0/0	0/0	0/1	2/2	0/3	1/2	0/2	2/2	0/0	0/0	1/2	1/2	A06,A11,B04,M09,N05,N06
	30	218	6	B,N	10/10	0/0	0/0	0/1	2/2	1/3	1/2	0/2	0/2	0/0	0/0	1/2	1/2	A11,B04,B10,M09,N05,N06
	20	187	4	B,N	8/10	0/0	0/0	0/1	2/2	1/3	1/2	0/2	0/2	0/0	0/0	0/2	0/2	B04,B10,N05,N06
13	60	99	3	F,L	5/6	0/0	0/0	0/0	0/0	1/2	1/2	1/1	0/2	0/0	0/1	0/0	0/0	B04,B10,G07
	50	99	3	D,F	5/6	0/0	0/0	0/0	0/0	1/2	1/2	1/1	0/2	0/0	0/1	0/0	0/0	B04,B10,G07
	40	99	3	A,G	5/6	0/0	0/0	0/0	0/0	1/2	1/2	1/1	0/2	0/0	0/1	0/0	0/0	B04,B10,G07
	30	88	3	E,G	5/6	0/0	0/0	0/0	0/0	0/2	1/2	1/1	2/2	0/0	0/1	0/0	0/0	A06,F07,G07
	20	99	3	B,G	5/6	0/0	0/0	0/0	0/0	1/2	1/2	1/1	0/2	0/0	0/1	0/0	0/0	B04,B10,G07
14	60	43	2	E,F	4/4	0/0	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	0/0	0/0	B04,E04
	50	43	2	E,F	4/4	0/0	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	0/0	0/0	B04,E04
	40	43	2	D,F	4/4	0/0	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	0/0	0/0	B04,E04
	30	43	2	D,G	4/4	0/0	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	0/0	0/0	B04,E04
	20	43	2	B,G	4/4	0/0	0/0	0/0	0/0	0/2	2/2	0/0	0/0	0/0	0/0	0/0	0/0	B04,F07
15	60	82	3	E,G	5/6	4/4	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	1/1	0/0	B04,I03,J02
	50	82	3	E,G	5/6	4/4	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	1/1	0/0	B04,I03,J02
	40	82	3	A,I	5/6	4/4	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	1/1	0/0	B04,I03,J02
	30	82	3	D,I	5/6	4/4	0/0	0/0	0/0	1/2	1/2	0/0	0/0	0/0	0/0	1/1	0/0	B04,I03,J02
	20	77	3	B,G	5/6	4/4	0/0	0/0	0/0	1/2	2/2	0/0	0/0	0/0	0/0	0/1	0/0	B04,F07,J02
16	60	853	9	D,J	14/14	26/26	0/0	1/1	2/2	2/3	1/2	0/0	2/2	1/2	0/1	2/2	0/1	B04,F05,F07,I03,J02,J09,M09,N02,N11
	50	853	9	E,G	14/14	26/26	0/0	1/1	2/2	2/3	1/2	0/0	2/2	1/2	0/1	2/2	0/1	B04,F05,F07,I03,J02,J09,M09,N02,N11
	40	847	9	I,L	14/14	26/26	0/0	1/1	2/2	2/3	0/2	0/0	2/2	2/2	0/1	2/2	0/1	E04,F05,F07,I03,J02,J09,M09,N02,N11
	30	842	8	G,L	14/14	26/26	0/0	1/1	2/2	2/3	0/2	0/0	2/2	2/2	0/1	1/2	0/1	E04,F05,F07,J02,J09,M09,N02,N11
	20	763	4	J,N	6/14	26/26	0/0	0/1	2/2	2/3	0/2	0/0	2/2	0/2	0/1	0/2	0/1	J02,J09,N02,N11
17	60	226	5	E,G	8/8	0/0	0/0	1/1	2/2	1/2	1/2	0/0	0/4	0/3	0/0	1/2	0/1	B04,H02,M09,N02,N11
	50	226	5	E,G	8/8	0/0	0/0	1/1	2/2	1/2	1/2	0/0	0/4	0/3	0/0	1/2	0/1	B04,H02,M09,N02,N11
	40	220	5	F,L	8/8	0/0	0/0	1/1	2/2	1/2	0/2	0/0	0/4	1/3	0/0	1/2	0/1	F05,H02,M09,N02,N11
	30	186	4	K,L	7/8	0/0	0/0	1/1	2/2	0/2	0/2	0/0	0/4	1/3	0/0	1/2	0/1	F07,M09,N02,N11
	20	160	3	J,N	6/8	0/0	0/0	0/1	2/2	1/2	0/2	0/0	0/4	0/3	0/0	0/2	0/1	J07,N02,N11
18	60	268	5	E,F	6/6	6/6	0/0	0/1	2/2	2/2	0/2	1/1	2/4	0/2	0/1	0/0	0/1	C10,H02,J09,N02,N11
	50	268	5	E,F	6/6	6/6	0/0	0/1	2/2	2/2	0/2	1/1	3/4	0/2	0/1	0/0	0/1	C10,J02,J09,N02,N11
	40	234	4	F,L	6/6	2/6	0/0	0/1	2/2	1/2	0/2	1/1	1/4	0/2	0/1	0/0	0/1	C10,J09,N02,N11
	30	234	4	K,L	5/6	4/6	0/0	0/1	2/2	1/2	0/2	1/1	3/4	0/2	0/1	0/0	0/1	J02,J09,N02,N11
	20	234	4	J,N	5/6	4/6	0/0	0/1	2/2	1/2	0/2	1/1	3/4	0/2	0/1	0/0	0/1	J02,J09,N02,N11
19	60	1590	5	E,G	10/10	44/44	0/0	0/2	2/2	1/1	1/2	0/0	4/4	0/1	0/0	0/3	0/0	B04,H05,H08,N02,N11
	50	1590	5	E,G	10/10	44/44	0/0	0/2	2/2	1/1	1/2	0/0	4/4	0/1	0/0	0/3	0/0	B04,H05,H08,N02,N11
	40	1494	5	D,G	10/10	44/44	0/0	0/2	0/2	1/1	2/2	0/0	4/4	1/1	0/0	0/3	0/0	B04,F05,F11,H05,H08
	30	1494	5	D,H	10/10	44/44	0/0	0/2	0/2	1/1	2/2	0/0	4/4	1/1	0/0	0/3	0/0	B04,F11,H05,H08,I04
	20	1446	3	B,H	6/10	44/44	0/0	0/2	0/2	1/1	1/2	0/0	4/4	0/1	0/0	0/3	0/0	B04,H05,H08,N02,N11
20	60	230	8	E,G	10/10	23/23	0/0	0/0	0/0	2/4	2/2	0/0	4/4	0/0	0/0	2/3	1/1	A11,B04,F05,G07,H02,I03,J07,J09
	50	230	8	D,G	10/10	23/23	0/0	0/0	0/0	2/4	2/2	0/0	4/4	0/0	0/0	2/3	1/1	A11,B04,F05,G07,H02,I03,J07,J09
	40	230	8	D,G	10/10	23/23	0/0	0/0	0/0	2/4	2/2	0/0	4/4	0/0	0/0	2/3	1/1	A11,B04,F05,G07,H02,I03,J07,J09
	30	220	7	H,K	9/10	23/23	0/0	0/0	0/0	2/4	2/2	0/0	4/4	0/0	0/0	2/3	0/1	F05,G07,H02,I03,I04,J07,K07
	20	186	6	I,J	9/10	4/23	0/0	0/0	0/0	1/4	2/2	0/0	2/4	0/0	0/0	2/3	0/1	G07,I03,I04,J07,J09,K04
21	60	131	5	E,G	9/10	2/2	0/0	0/0	0/0	2/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	A09,B04,C04,C10,E04
	50	131	5	D,G	9/10	2/2	0/0	0/0	0/0	2/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	A09,B04,C04,C10,E04
	40	115	4	B,G	7/10	2/2	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	A09,B04,C04,C10
	30	115	4	C,K	7/10	2/2	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	B04,C04,C10,F05
	20	115	4	C,G	7/10	2/2	0/0	0/0	0/0	1/2	3/3	0/0	0/0	0/0	0/0	0/0	0/0	B04,C04,C10,F05

Appendix F: Actual Schedule vs. Model Solution Sensitivity Analysis

May	Time	Weight	LFs	MAF	SETS	Other	BATT	CCT	CE	EMT	FMT	MHT	MMT	PMT	PNEU	RVM	TRN	LFs
	60	238	8	E,G	15/16	0/0	0/0	1/1	0/0	2/2	2/2	0/0	0/0	0/0	0/0	3/3	0/0	A09,B04,G07,I03,I04,J09,K07,M09
	50	238	8	E,G	15/16	0/0	0/0	1/1	0/0	2/2	2/2	0/0	0/0	0/0	0/0	3/3	0/0	A09,B04,G07,I03,I04,J09,K07,M09
22	40	206	7	E,G	14/16	0/0	0/0	0/1	0/0	2/2	2/2	0/0	0/0	0/0	0/0	3/3	0/0	A09,E04,G07,I03,I04,J09,K07
	30	195	7	H,L	13/16	0/0	0/0	1/1	0/0	2/2	2/2	0/0	0/0	0/0	0/0	2/3	0/0	E04,G07,H09,I03,I04,K07,M09
	20	174	6	I,K	12/16	0/0	0/0	0/1	0/0	2/2	2/2	0/0	0/0	0/0	0/0	2/3	0/0	G05,G07,I02,I03,I04
	60	1325	8	E,G	14/14	37/37	0/0	1/1	0/0	3/3	2/2	0/0	4/4	0/1	0/1	3/3	0/1	B04,G05,G07,I03,I04,J09,K07,M09
	50	1325	8	E,G	14/14	37/37	0/0	1/1	0/0	3/3	2/2	0/0	4/4	0/1	0/1	3/3	0/1	B04,G05,G07,I03,I04,J09,K07,M09
23	40	1309	8	A,G	14/14	37/37	0/0	0/1	0/0	3/3	2/2	0/0	4/4	0/1	0/1	2/3	1/1	A09,A11,E04,G05,G07,I03,I04,J09
	30	1293	7	H,L	13/14	37/37	0/0	1/1	0/0	3/3	1/2	0/0	4/4	0/1	0/1	2/3	0/1	G05,G07,I02,I03,I04,K07,M09
	20	1251	5	G,I	10/14	37/37	0/0	0/1	0/0	3/3	1/2	0/0	4/4	0/1	0/1	1/3	0/1	G05,G07,I02,I03,I04
	60	165	7	E,G	12/12	0/0	0/0	1/2	0/0	0/1	3/3	0/1	0/0	0/0	0/0	4/4	0/2	A09,C07,I03,J08,J09,K07,M09
	50	165	7	E,G	12/12	0/0	0/0	1/2	0/0	0/1	3/3	0/1	0/0	0/0	0/0	4/4	0/2	A09,C07,I03,J08,J09,K07,M09
24	40	154	7	B,L	12/12	0/0	0/0	1/2	0/0	0/1	3/3	0/1	0/0	0/0	0/0	3/4	1/2	A09,C07,E04,J08,J09,K07,M09
	30	132	7	J,L	12/12	0/0	0/0	1/2	0/0	0/1	3/3	0/1	0/0	0/0	0/0	3/4	1/2	E04,G08,J08,J09,K02,K07,M09
	20	85	4	J,K	7/12	0/0	0/0	0/2	0/0	0/1	2/3	0/1	0/0	0/0	0/0	2/4	0/2	J08,J09,K02,K07
	60	495	7	E,J	14/16	0/0	0/0	1/1	0/0	1/1	2/2	0/1	4/4	0/0	0/0	1/2	1/2	A06,A11,C07,J08,J09,K07,K11
	50	495	7	D,J	14/16	0/0	0/0	1/1	0/0	1/1	2/2	0/1	4/4	0/0	0/0	1/2	1/2	A06,A11,C07,J08,J09,K07,K11
25	40	495	7	D,L	14/16	0/0	0/0	1/1	0/0	1/1	2/2	0/1	4/4	0/0	0/0	1/2	1/2	A06,A11,C07,J08,J09,K07,K11
	30	458	5	K,M	11/16	0/0	0/0	1/1	0/0	1/1	2/2	0/1	2/4	0/0	0/0	1/2	0/2	J08,J09,K07,K11,M06
	20	400	2	E,F	6/16	0/0	0/0	0/1	0/0	1/1	1/2	0/1	2/4	0/0	0/0	0/2	0/2	C07,K11
	60	797	4	J,L	7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4	0/0	0/0	0/1	0/0	J08,K09,L04,M09
	50	797	4	J,O	7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4	0/0	0/0	0/1	0/0	J08,K09,L04,M09
26	40	797	4	I,L	7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4	0/0	0/0	0/1	0/0	J08,K09,L04,M09
	30	797	4	K,M	7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4	0/0	0/0	0/1	0/0	J08,K09,L04,M09
	20	426	4	J,K	7/7	15/15	0/0	1/1	0/0	1/2	1/2	0/1	2/4	0/0	0/0	1/1	0/0	J08,J09,K07,L07

Appendix G: Sensitivity Analysis of Response Time vs. Team Utilization Rates

	Available vs. Utilized SETS										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	22	16	72.73	14	63.64	12	54.55	12	54.55	9	40.91
2-May	18	17	94.44	15	83.33	15	83.33	13	72.22	9	50.00
3-May	17	17	100.00	17	100.00	17	100.00	12	70.59	5	29.41
4-May	28	21	75.00	17	60.71	15	53.57	13	46.43	11	39.29
5-May	19	18	94.74	13	68.42	13	68.42	13	68.42	10	52.63
6-May	12	12	100.00	12	100.00	12	100.00	10	83.33	6	50.00
7-May	10	8	80.00	8	80.00	8	80.00	8	80.00	4	40.00
8-May	10	2	20.00	2	20.00	2	20.00	2	20.00	2	20.00
9-May	15	15	100.00	15	100.00	15	100.00	10	66.67	4	26.67
10-May	5	5	100.00	5	100.00	5	100.00	5	100.00	5	100.00
11-May	9	9	100.00	11	122.22	11	122.22	11	122.22	6	66.67
12-May	10	10	100.00	10	100.00	10	100.00	10	100.00	8	80.00
13-May	5	5	100.00	5	100.00	5	100.00	5	100.00	5	100.00
14-May	4	4	100.00	6	150.00	6	150.00	6	150.00	4	100.00
15-May	5	5	100.00	5	100.00	5	100.00	5	100.00	5	100.00
16-May	14	14	100.00	16	114.29	16	114.29	14	100.00	6	42.86
17-May	8	8	100.00	8	100.00	8	100.00	8	100.00	7	87.50
18-May	6	6	100.00	6	100.00	6	100.00	5	83.33	5	83.33
19-May	10	10	100.00	10	100.00	10	100.00	10	100.00	6	60.00
20-May	10	10	100.00	10	100.00	10	100.00	9	90.00	9	90.00
21-May	9	9	100.00	9	100.00	7	77.78	7	77.78	7	77.78
22-May	16	15	93.75	15	93.75	14	87.50	13	81.25	12	75.00
23-May	14	14	100.00	14	100.00	14	100.00	13	92.86	10	71.43
24-May	12	12	100.00	12	100.00	12	100.00	12	100.00	7	58.33
25-May	14	14	100.00	14	100.00	14	100.00	11	78.57	6	42.86
26-May	7	7	100.00	7	100.00	7	100.00	7	100.00	7	100.00
Average	11.88	10.88	93.49	10.62	94.48	10.35	92.76	9.38	86.09	6.73	67.73
Rounded	12	11	94	11	95	11	93	87	7	68	68

	Available vs. Other Guards										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	15	15	100.00	15	100.00	15	100.00	15	100.00	15	100.00
2-May	15	15	100.00	15	100.00	15	100.00	15	100.00	15	100.00
3-May	22	15	68.18	15	22.00	15	68.18	15	22.00	15	68.18
4-May	0	0	*	0	*	0	*	0	*	0	*
5-May	0	0	*	0	*	0	*	0	*	0	*
6-May	22	22	100.00	22	100.00	22	100.00	22	100.00	22	100.00
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	37	37	100.00	37	100.00	37	100.00	37	100.00	37	100.00
10-May	0	0	*	0	*	0	*	0	*	0	*
11-May	0	0	*	0	*	0	*	0	*	0	*
12-May	0	0	*	0	*	0	*	0	*	0	*
13-May	0	0	*	0	*	0	*	0	*	0	*
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	4	4	100.00	4	100.00	4	100.00	4	100.00	4	100.00
16-May	26	26	100.00	26	100.00	26	100.00	26	100.00	26	100.00
17-May	0	0	*	0	*	0	*	0	*	0	*
18-May	6	6	100.00	6	100.00	2	33.33	4	66.67	4	66.67
19-May	44	44	100.00	44	100.00	44	100.00	44	100.00	44	100.00
20-May	19	6	31.58	6	31.58	6	31.58	4	21.05	4	21.05
21-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	37	37	100.00	37	100.00	37	100.00	37	100.00	37	100.00
24-May	0	0	*	0	*	0	*	0	*	0	*
25-May	0	0	*	0	*	0	*	0	*	0	*
26-May	15	15	100.00	15	100.00	15	100.00	15	100.00	15	100.00
Average	10.15	9.38	92.29	9.38	88.74	9.23	87.16	9.23	85.36	9.23	88.92
Rounded	11	10	93	10	89	10	88	10	86	10	89

Appendix G: Sensitivity Analysis of Response Time on Team Utilization Rates

	Available vs. Utilized BATT									
Response Time		60		50		40		30		20
Date	Available	Actual	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	0	0	*	0	*	0	*	0	*	0	*
2-May	0	0	*	0	*	0	*	0	*	0	*
3-May	0	0	*	0	*	0	*	0	*	0	*
4-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
5-May	0	0	*	0	*	0	*	0	*	0	*
6-May	0	0	*	0	*	0	*	0	*	0	*
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	0	0	*	0	*	0	*	0	*	0	*
10-May	0	0	*	0	*	0	*	0	*	0	*
11-May	0	0	*	0	*	0	*	0	*	0	*
12-May	0	0	*	0	*	0	*	0	*	0	*
13-May	0	0	*	0	*	0	*	0	*	0	*
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	0	0	*	0	*	0	*	0	*	0	*
17-May	0	0	*	0	*	0	*	0	*	0	*
18-May	0	0	*	0	*	0	*	0	*	0	*
19-May	0	0	*	0	*	0	*	0	*	0	*
20-May	0	0	*	0	*	0	*	0	*	0	*
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	0	0	*	0	*	0	*	0	*	0	*
24-May	0	0	*	0	*	0	*	0	*	0	*
25-May	0	0	*	0	*	0	*	0	*	0	*
26-May	0	0	*	0	*	0	*	0	*	0	*
Average	1.00	1.00	100.00	1.00	100.00	1.00	100.00	1.00	100.00	1.00	100.00
Rounded	1	1	100	1	100	1	100	1	100	1	100

	Available vs. Utilized CCT									
Response Time		60		50		40		30		20
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
2-May	2	2	100.00	2	100.00	1	50.00	1	50.00	0	0.00
3-May	2	2	100.00	2	100.00	2	100.00	1	50.00	0	0.00
4-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
5-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
6-May	0	0	*	0	*	0	*	0	*	0	*
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
10-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
11-May	0	0	*	0	*	0	*	0	*	0	*
12-May	1	1	100.00	0	0.00	0	0.00	0	0.00	0	0.00
13-May	0	0	*	0	*	0	*	0	*	0	*
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	2	1	50.00	1	50.00	1	50.00	1	50.00	0	0.00
17-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
18-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
19-May	2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
20-May	0	0	*	0	*	0	*	0	*	0	*
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	1	1	100.00	1	100.00	0	0.00	1	100.00	0	0.00
23-May	1	1	100.00	1	100.00	0	0.00	1	100.00	0	0.00
24-May	2	1	50.00	1	50.00	1	50.00	1	50.00	0	0.00
25-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
26-May	1	0	0.00	0	0.00	0	0.00	0	0.00	1	100.00
Average	1.29	0.88	70.59	0.82	64.71	0.65	50.00	0.71	58.82	0.18	17.65
Rounded	2	1	71	1	65	1	50	1	59	1	18

Appendix G: Sensitivity Analysis of Response Time on Team Utilization Rates

	Available vs. Utilized CE										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	0	0	*	0	*	0	*	0	*	0	*
2-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
3-May	2	2	100.00	2	100.00	0	0.00	0	0.00	0	0.00
4-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
5-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
6-May	0	0	*	0	*	0	*	0	*	0	*
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	2	2	100.00	2	100.00	2	100.00	0	0.00	0	0.00
10-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
11-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
12-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
13-May	0	0	*	0	*	0	*	0	*	0	*
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
17-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
18-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
19-May	2	2	100.00	2	100.00	0	0.00	0	0.00	0	0.00
20-May	0	0	*	0	*	0	*	0	*	0	*
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	0	0	*	0	*	0	*	0	*	0	*
24-May	0	0	*	0	*	0	*	0	*	0	*
25-May	0	0	*	0	*	0	*	0	*	0	*
26-May	0	0	*	0	*	0	*	0	*	0	*
Average	2.00	2.00	100.00	2.00	100.00	1.67	83.33	1.50	75.00	1.50	75.00
Rounded	2	2	100	2	100	2	83	2	75	2	75

	Available vs. Utilized EMT										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	2	2	100.00	1	50.00	2	100.00	2	100.00	2	100.00
2-May	3	2	66.67	2	66.67	3	100.00	2	66.67	2	66.67
3-May	3	1	33.33	1	33.33	1	33.33	1	33.33	1	33.33
4-May	3	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
5-May	2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
6-May	6	2	33.33	2	33.33	2	33.33	2	33.33	2	33.33
7-May	2	1	50.00	1	50.00	1	50.00	1	50.00	0	0.00
8-May	2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
9-May	3	2	66.67	2	66.67	2	66.67	2	66.67	2	66.67
10-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
11-May	2	1	50.00	2	100.00	1	50.00	1	50.00	0	0.00
12-May	3	0	0.00	0	0.00	0	0.00	1	33.33	1	33.33
13-May	2	1	50.00	1	50.00	1	50.00	0	0.00	1	50.00
14-May	2	1	50.00	1	50.00	1	50.00	1	50.00	0	0.00
15-May	2	1	50.00	1	50.00	1	50.00	1	50.00	1	50.00
16-May	4	2	50.00	2	50.00	3	75.00	3	75.00	2	50.00
17-May	2	0	0.00	0	0.00	0	0.00	0	0.00	2	100.00
18-May	2	2	100.00	2	100.00	1	50.00	1	50.00	1	50.00
19-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
20-May	4	2	50.00	2	50.00	2	50.00	1	25.00	1	25.00
21-May	2	2	100.00	2	100.00	1	50.00	1	50.00	1	50.00
22-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
23-May	3	3	100.00	3	100.00	3	100.00	3	100.00	3	100.00
24-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
25-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
26-May	2	2	100.00	2	100.00	2	100.00	2	100.00	1	50.00
Average	2.38	1.19	51.92	1.19	51.92	1.19	50.32	1.12	47.44	1.04	44.55
Rounded	2	1	52	1	52	1	50	1	47	1	45

Appendix G: Sensitivity Analysis of Response Time on Team Utilization Rates

	Available vs. Utilized FMT										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	3	3	100.00	3	100.00	1	33.33	1	33.33	1	33.33
2-May	3	2	66.67	1	33.33	1	33.33	1	33.33	0	0.00
3-May	2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
4-May	2	2	100.00	2	100.00	2	100.00	2	100.00	0	0.00
5-May	2	2	100.00	2	100.00	2	100.00	2	100.00	1	50.00
6-May	2	2	100.00	2	100.00	2	100.00	2	100.00	1	50.00
7-May	3	3	100.00	3	100.00	3	100.00	3	100.00	2	66.67
8-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
9-May	2	2	100.00	2	100.00	2	100.00	1	50.00	0	0.00
10-May	2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
11-May	2	2	100.00	0	0.00	2	100.00	2	100.00	1	50.00
12-May	2	1	50.00	1	50.00	1	50.00	1	50.00	1	50.00
13-May	2	1	50.00	1	50.00	1	50.00	1	50.00	1	50.00
14-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
15-May	2	1	50.00	1	50.00	1	50.00	1	50.00	2	100.00
16-May	2	1	50.00	1	50.00	0	0.00	0	0.00	0	0.00
17-May	2	1	50.00	1	50.00	1	50.00	0	0.00	0	0.00
18-May	2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
19-May	2	1	50.00	1	50.00	2	100.00	2	100.00	1	50.00
20-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
21-May	3	3	100.00	3	100.00	3	100.00	3	100.00	3	100.00
22-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
23-May	2	2	100.00	2	100.00	2	100.00	1	50.00	1	50.00
24-May	3	3	100.00	3	100.00	3	100.00	3	100.00	2	66.67
25-May	2	2	100.00	2	100.00	2	100.00	2	100.00	1	50.00
26-May	2	1	50.00	1	50.00	1	50.00	1	50.00	1	50.00
Average	2.15	1.62	73.72	1.50	68.59	1.50	69.87	1.38	64.10	1.00	46.79
Rounded	2	2	74	2	69	2	70	1	64	1	47

	Available vs. Utilized MHT										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	0	0	*	0	*	0	*	0	*	0	*
2-May	0	0	*	0	*	0	*	0	*	0	*
3-May	1	1	100.00	1	100.00	1	100.00	0	0.00	0	0.00
4-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
5-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
6-May	0	0	*	0	*	0	*	0	*	0	*
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	0	0	*	0	*	0	*	0	*	0	*
10-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
11-May	0	0	*	0	*	0	*	0	*	0	*
12-May	0	0	*	0	*	0	*	0	*	0	*
13-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	0	0	*	0	*	0	*	0	*	0	*
17-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
18-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
19-May	0	0	*	0	*	0	*	0	*	0	*
20-May	0	0	*	0	*	0	*	0	*	0	*
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	0	0	*	0	*	0	*	0	*	0	*
24-May	0	0	*	0	*	0	*	0	*	0	*
25-May	0	0	*	0	*	0	*	0	*	0	*
26-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
Average	0.31	0.31	100.00	0.31	100.00	0.31	100.00	0.27	87.50	0.23	75.00
Rounded	0	0	100	0	100	0	100	0	88	0	75

Appendix G: Sensitivity Analysis of Response Time on Team Utilization Rates

	Available vs. Utilized MMT										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
2-May	4	4	100.00	4	100.00	4	100.00	4	100.00	4	100.00
3-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
4-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
5-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
6-May	4	4	100.00	4	100.00	4	100.00	2	50.00	2	50.00
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	5	4	80.00	4	80.00	4	80.00	4	80.00	4	80.00
10-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
11-May	2	0	0.00	2	100.00	0	0.00	0	0.00	0	0.00
12-May	2	0	0.00	2	100.00	2	100.00	0	0.00	0	0.00
13-May	2	0	0.00	0	0.00	0	0.00	2	100.00	0	0.00
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
17-May	4	1	25.00	1	25.00	1	25.00	1	25.00	1	25.00
18-May	4	2	50.00	3	75.00	1	25.00	3	75.00	3	75.00
19-May	4	4	100.00	4	100.00	4	100.00	4	100.00	4	100.00
20-May	4	2	50.00	2	50.00	2	50.00	2	50.00	2	50.00
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	4	4	100.00	4	100.00	4	100.00	4	100.00	4	100.00
24-May	0	0	*	0	*	0	*	0	*	0	*
25-May	4	4	100.00	4	100.00	4	100.00	2	50.00	2	50.00
26-May	4	4	100.00	4	100.00	4	100.00	4	100.00	2	50.00
Average	2.15	1.62	73.95	1.81	85.79	1.65	77.89	1.58	75.26	1.42	67.37
Rounded	2	2	74	2	86	2	78	2	75	1	67

	Available vs. Utilized PMT										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	0	0	*	0	*	0	*	0	*	0	*
2-May	0	0	*	0	*	0	*	0	*	0	*
3-May	3	2	66.67	2	66.67	3	100.00	2	66.67	0	0.00
4-May	3	3	100.00	2	66.67	1	33.33	0	0.00	1	33.33
5-May	3	2	66.67	0	0.00	0	0.00	0	0.00	0	0.00
6-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	0	0	*	0	*	0	*	0	*	0	*
10-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
11-May	0	0	*	0	*	0	*	0	*	0	*
12-May	0	0	*	0	*	0	*	0	*	0	*
13-May	0	0	*	0	*	0	*	0	*	0	*
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	2	2	100.00	2	100.00	2	100.00	0	0.00	0	0.00
17-May	3	0	0.00	0	0.00	0	0.00	1	33.33	0	0.00
18-May	2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
19-May	1	0	0.00	0	0.00	1	100.00	1	100.00	0	0.00
20-May	0	0	*	0	*	0	*	0	*	0	*
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
24-May	0	0	*	0	*	0	*	0	*	0	*
25-May	0	0	*	0	*	0	*	0	*	0	*
26-May	0	0	*	0	*	0	*	0	*	0	*
Average	0.77	0.38	43.33	0.27	33.33	0.31	43.33	0.19	30.00	0.04	3.33
Rounded	1	0	43	0	33	0	43	0	30	0	3

Appendix G: Sensitivity Analysis of Response Time on Team Utilization Rates

	Available vs. Utilized PNEU										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
2-May	0	0	*	0	*	0	*	0	*	0	*
3-May	0	0	*	0	*	0	*	0	*	0	*
4-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
5-May	0	0	*	0	*	0	*	0	*	0	*
6-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	0	0	*	0	*	0	*	0	*	0	*
10-May	0	0	*	0	*	0	*	0	*	0	*
11-May	0	0	*	0	*	0	*	0	*	0	*
12-May	0	0	*	0	*	0	*	0	*	0	*
13-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	0	0	*	0	*	0	*	0	*	0	*
17-May	0	0	*	0	*	0	*	0	*	0	*
18-May	0	0	*	0	*	0	*	0	*	0	*
19-May	0	0	*	0	*	0	*	0	*	0	*
20-May	0	0	*	0	*	0	*	0	*	0	*
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	0	0	*	0	*	0	*	0	*	0	*
24-May	0	0	*	0	*	0	*	0	*	0	*
25-May	0	0	*	0	*	0	*	0	*	0	*
26-May	0	0	*	0	*	0	*	0	*	0	*
Average	0.15	0.04	25.00	0.04	25.00	0.04	25.00	0.04	25.00	0.00	0.00
Rounded	0	0	25	0	25	0	25	0	25	0	0

	Available vs. Utilized RVM										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	2	2	100.00	2	100.00	2	100.00	2	100.00	2	100.00
2-May	2	2	100.00	2	100.00	1	50.00	1	50.00	1	50.00
3-May	3	2	66.67	2	66.67	3	100.00	3	100.00	2	66.67
4-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
5-May	2	2	100.00	2	100.00	2	100.00	2	100.00	1	50.00
6-May	0	0	*	0	*	0	*	0	*	0	*
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	2	2	100.00	2	100.00	1	50.00	2	100.00	0	0.00
10-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
11-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
12-May	2	2	100.00	1	50.00	1	50.00	1	50.00	0	0.00
13-May	0	0	*	0	*	0	*	0	*	0	*
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
16-May	2	2	100.00	2	100.00	2	100.00	1	50.00	0	0.00
17-May	2	1	50.00	1	50.00	1	50.00	1	50.00	0	0.00
18-May	0	0	*	0	*	0	*	0	*	0	*
19-May	3	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
20-May	3	2	66.67	2	66.67	2	66.67	2	66.67	2	66.67
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	3	3	100.00	3	100.00	3	100.00	2	66.67	2	66.67
23-May	3	3	100.00	3	100.00	2	66.67	2	66.67	1	33.33
24-May	4	4	100.00	4	100.00	3	75.00	3	75.00	2	50.00
25-May	2	1	50.00	1	50.00	1	50.00	0	0.00	0	0.00
26-May	1	0	0.00	0	0.00	0	0.00	0	0.00	1	100.00
Average	1.54	1.19	75.44	1.15	72.81	1.04	66.23	0.96	61.84	0.58	35.96
Rounded	2	1	75	1	73	1	66	1	62	1	36

Appendix G: Sensitivity Analysis of Response Time on Team Utilization Rates

	Available vs. Utilized TRN										
Response Time		60		50		40		30		20	
Date	Available	Model	Utilization	Model	Utilization	Model	Utilization	Actual	Utilization	Actual	Utilization
1-May	0	0	*	0	*	0	*	0	*	0	*
2-May	0	0	*	0	*	0	*	0	*	0	*
3-May	1	1	100.00	1	100.00	1	100.00	1	100.00	0	0.00
4-May	0	0	*	0	*	0	*	0	*	0	*
5-May	1	1	100.00	0	0.00	0	0.00	0	0.00	0	0.00
6-May	1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00
7-May	0	0	*	0	*	0	*	0	*	0	*
8-May	0	0	*	0	*	0	*	0	*	0	*
9-May	0	0	*	0	*	0	*	0	*	0	*
10-May	0	0	*	0	*	0	*	0	*	0	*
11-May	0	0	*	0	*	0	*	0	*	0	*
12-May	0	0	*	0	*	0	*	0	*	0	*
13-May	0	0	*	0	*	0	*	0	*	0	*
14-May	0	0	*	0	*	0	*	0	*	0	*
15-May	0	0	*	0	*	0	*	0	*	0	*
16-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
17-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
18-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
19-May	0	0	*	0	*	0	*	0	*	0	*
20-May	1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
21-May	0	0	*	0	*	0	*	0	*	0	*
22-May	0	0	*	0	*	0	*	0	*	0	*
23-May	0	0	*	0	*	0	*	0	*	0	*
24-May	1	0	0.00	0	0.00	1	100.00	1	100.00	0	0.00
25-May	1	1	100.00	1	100.00	1	100.00	0	0.00	0	0.00
26-May	0	0	*	0	*	0	*	0	*	0	*
Average	0.35	0.15	44.44	0.12	33.33	0.15	44.44	0.12	33.33	0.04	11.11
Rounded	0	0	44	0	33	0	44	0	33	0	11

Appendix H: Sensitivity Analysis of Changing Quantity of Security Umbrellas

Date	Response Time	5 Umbrellas		4 Umbrellas		3 Umbrellas		2 Umbrellas		1 Umbrella	
		Weights	LFs	Weights	LFs	Weights	LFs	Weights	LFs	Weights	LFs
1 May 05	60	540	9	540	9	540	9	540	9	513	8
	50	540	9	540	9	540	9	506	8	463	6
	40	540	9	540	9	540	9	497	7	442	5
	30	540	9	540	9	540	9	497	7	421	4
	20	508	7	508	7	487	6	460	5	405	3
2 May 05	60	673	10	673	10	673	10	673	10	657	9
	50	673	10	673	10	673	10	657	9	441	5
	40	673	10	673	10	663	10	621	8	421	5
	30	673	10	673	10	657	9	615	7	378	2
	20	657	9	638	8	620	7	578	5	378	2
3 May 05	60	753	10	753	10	753	10	753	10	753	10
	50	753	10	753	10	753	10	753	10	630	9
	40	753	10	753	10	753	10	651	10	503	7
	30	753	10	753	10	753	10	553	7	490	4
	20	732	9	655	7	578	5	434	3	378	2
4 May 05	60	367	12	367	12	367	12	367	12	361	11
	50	367	12	367	12	367	12	340	10	257	9
	40	367	12	367	12	367	12	319	9	232	5
	30	367	12	346	11	340	10	298	8	232	5
	20	361	11	345	10	303	8	276	7	200	3
5 May 05	60	358	11	358	11	358	11	358	11	327	9
	50	358	11	358	11	358	11	306	8	234	7
	40	358	11	358	11	358	11	306	8	216	4
	30	358	11	358	11	348	10	306	8	216	4
	20	342	10	321	9	311	8	269	6	200	3
6 May 05	60	686	6	686	6	686	6	686	6	676	6
	50	686	6	686	6	686	6	686	6	675	6
	40	686	6	686	6	686	6	686	6	660	6
	30	686	6	686	6	670	5	670	5	638	4
	20	686	6	670	5	659	5	622	3	622	3
7 May 05	60	75	4	75	4	75	4	75	4	75	4
	50	75	4	75	4	75	4	75	4	59	3
	40	75	4	75	4	75	4	75	4	48	3
	30	75	4	75	4	75	4	75	4	43	2
	20	75	4	75	4	59	3	43	2	27	1
8 May 05	60	27	1	27	1	27	1	27	1	27	1
	50	27	1	27	1	27	1	27	1	27	1
	40	27	1	27	1	27	1	27	1	27	1
	30	27	1	27	1	27	1	27	1	27	1
	20	27	1	27	1	27	1	27	1	27	1
9 May 05	60	1192	9	1192	9	1192	9	1192	9	1160	8
	50	1192	9	1192	9	1192	9	1181	9	1139	7
	40	1192	9	1192	9	1192	9	1171	8	782	6
	30	1192	9	1192	9	1192	9	1021	6	638	4
	20	1128	6	1128	6	1086	4	942	2	585	1
10 May 05	60	200	3	200	3	200	3	200	3	165	3
	50	200	3	200	3	200	3	200	3	165	3
	40	200	3	200	3	200	3	200	3	165	3
	30	200	3	200	3	200	3	200	3	165	3
	20	200	3	200	3	200	3	200	3	144	2

Appendix H: Sensitivity Analysis of Changing Quantity of Security Umbrellas

Date	Response Time	5 Umbrellas		4 Umbrellas		3 Umbrellas		2 Umbrellas		1 Umbrella	
		Weights	LFs	Weights	LFs	Weights	LFs	Weights	LFs	Weights	LFs
11 May 05	60	213	5	213	5	213	5	213	5	208	5
	50	213	5	213	5	213	5	202	5	197	5
	40	213	5	213	5	213	5	208	5	197	5
	30	213	5	213	5	213	5	208	5	181	4
	20	213	5	208	5	187	4	171	3	144	2
12 May 05	60	234	6	234	6	234	6	234	6	218	6
	50	234	6	234	6	234	6	218	6	197	5
	40	234	6	234	6	234	6	218	6	197	5
	30	234	6	229	6	229	6	218	6	165	3
	20	234	6	213	5	213	5	187	4	144	2
13 May 05	60	99	3	99	3	99	3	99	3	99	3
	50	99	3	99	3	99	3	99	3	99	3
	40	99	3	99	3	99	3	99	3	59	3
	30	99	3	99	3	99	3	88	3	72	2
	20	99	3	99	3	99	3	99	3	72	2
14 May 05	60	43	2	43	2	43	2	43	2	43	2
	50	43	2	43	2	43	2	43	2	43	2
	40	43	2	43	2	43	2	43	2	43	2
	30	43	2	43	2	43	2	43	2	43	2
	20	43	2	43	2	43	2	43	2	32	2
15 May 05	60	82	3	82	3	82	3	82	3	82	3
	50	82	3	82	3	82	3	82	3	77	3
	40	82	3	82	3	82	3	82	3	71	3
	30	82	3	82	3	82	3	82	3	71	3
	20	82	3	82	3	82	3	77	3	66	3
16 May 05	60	853	8	853	8	853	8	853	8	847	8
	50	853	8	853	8	853	8	853	8	770	7
	40	853	8	853	8	853	8	847	8	682	5
	30	853	8	853	8	847	8	842	8	661	4
	20	837	7	805	6	805	6	763	4	619	2
17 May 05	60	226	5	226	5	226	5	226	5	220	5
	50	226	5	226	5	226	5	226	5	186	4
	40	226	5	226	5	226	5	220	5	186	4
	30	226	5	226	5	220	5	186	4	186	4
	20	205	4	199	4	186	4	160	3	144	2
18 May 05	60	268	5	268	5	268	5	268	5	268	5
	50	268	5	268	5	268	5	268	5	234	4
	40	268	5	268	5	268	5	234	4	200	3
	30	268	5	268	5	268	5	234	4	160	3
	20	268	5	268	5	268	5	234	4	144	2
19 May 05	60	1590	5	1590	5	1590	5	1590	5	1590	5
	50	1590	5	1590	5	1590	5	1590	5	1245	5
	40	1590	5	1590	5	1590	5	1494	5	1245	5
	30	1590	5	1590	5	1590	5	1494	5	1218	4
	20	1590	5	1590	5	1590	5	1446	3	1170	2
20 May 05	60	230	8	230	8	230	8	230	8	220	7
	50	230	8	230	8	230	8	230	8	220	7
	40	230	8	230	8	230	8	230	8	220	7
	30	230	8	230	8	220	7	220	7	154	5
	20	220	7	220	7	220	7	186	6	104	3

Appendix H: Sensitivity Analysis of Changing Quantity of Security Umbrellas

Date	Response Time	5 Umbrellas		4 Umbrellas		3 Umbrellas		2 Umbrellas		1 Umbrella	
		Weights	LFs	Weights	LFs	Weights	LFs	Weights	LFs	Weights	LFs
21 May 05	60	131	5	131	5	131	5	131	5	131	5
	50	131	5	131	5	131	5	131	5	131	5
	40	131	5	131	5	131	5	115	4	115	4
	30	131	5	115	4	115	4	115	4	88	3
	20	115	4	115	4	115	4	115	4	88	3
22 May 05	60	238	8	238	8	238	8	238	8	206	7
	50	238	8	238	8	238	8	238	8	216	8
	40	238	8	238	8	238	8	206	7	174	6
	30	238	8	217	7	206	7	195	7	153	5
	20	217	7	206	7	195	7	174	6	137	4
23 May 05	60	1325	8	1325	8	1325	8	1325	8	1309	8
	50	1325	8	1325	8	1325	8	1325	8	1314	8
	40	1325	8	1325	8	1325	8	1309	8	1272	6
	30	1325	8	1304	7	1314	8	1293	7	1251	5
	20	1299	7	1299	7	1288	7	1251	5	1170	2
24 May 05	60	165	7	165	7	165	7	165	7	154	7
	50	165	7	165	7	165	7	165	7	143	7
	40	165	7	165	7	165	7	154	7	122	6
	30	165	7	154	7	143	7	132	7	85	4
	20	154	7	133	6	122	6	85	4	48	2
25 May 05	60	495	7	495	7	495	7	495	7	485	6
	50	495	7	495	7	495	7	495	7	458	5
	40	495	7	495	7	495	7	495	7	458	5
	30	495	7	495	7	469	5	458	5	442	4
	20	474	6	458	5	448	4	400	2	400	2
26 May 05	60	797	4	797	4	797	4	797	4	797	4
	50	797	4	797	4	797	4	797	4	797	4
	40	797	4	797	4	797	4	797	4	797	4
	30	797	4	797	4	797	4	797	4	797	4
	20	797	4	762	4	762	4	426	4	48	2

Appendix I: Post Analysis Comparisons

May		Wt	LFs	SETS	Other	BATT	CCT	CE	EMT	FMT	MHT	MMT
1	A	524	8	14/22	15/15	0/0	1/1	0/0	2/2	2/3	0/0	2/2
	M	513	8	14/22	15/15	0/0	1/1	0/0	2/2	2/3	0/0	2/2
2	A	657	9	15/18	15/15	0/0	2/2	2/2	2/3	1/3	0/0	4/4
	M	657	9	15/18	15/15	0/0	2/2	2/2	2/3	1/3	0/0	4/4
3	A	662	8	17/17	0/22	0/0	0/2	2/2	1/3	0/2	1/1	2/2
	M	683	10	17/17	22/22	0/0	2/2	2/2	1/3	0/2	1/1	2/2
4	A	294	10	19/28	0/0	1/1	1/1	2/2	0/3	1/2	1/1	1/1
	M	350	11	19/28	0/0	1/1	1/1	2/2	0/3	2/2	1/1	1/1
5	A	300	9	15/19	0/0	0/0	1/1	2/2	1/2	0/2	1/1	1/1
	M	337	10	17/19	0/0	0/0	1/1	2/2	0/2	2/2	1/1	1/1
6	A	665	6	12/12	22/22	0/0	0/0	0/0	4/6	2/2	0/0	2/4
	M	676	6	12/12	22/22	0/0	0/0	0/0	3/6	2/2	0/0	4/4
7	A	75	4	8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0
	M	75	4	8/10	0/0	0/0	0/0	0/0	1/2	3/3	0/0	0/0
8	A	27	1	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0
	M	27	1	2/10	0/0	0/0	0/0	0/0	0/2	1/1	0/0	0/0
9	A	1165	8	15/15	37/37	0/0	1/1	2/2	2/3	1/2	0/0	4/5
	M	1181	9	15/15	37/37	0/0	1/1	2/2	2/3	2/2	0/0	4/5
10	A	200	3	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1
	M	200	3	5/5	0/0	0/0	0/1	2/2	0/1	0/2	1/1	1/1
11	A	202	5	9/9	0/0	0/0	0/0	2/2	1/2	0/2	0/0	0/2
	M	208	5	9/9	0/0	0/0	0/0	2/2	0/2	1/2	0/0	2/2
12	A	208	5	10/10	0/0	0/0	0/1	2/2	0/3	2/2	0/0	0/2
	M	223	6	10/10	0/0	0/0	1/1	2/2	1/3	0/2	0/0	0/2
13	A	88	3	5/5	0/0	0/0	0/0	0/0	1/2	0/2	1/1	1/2
	M	99	3	5/5	0/0	0/0	0/0	0/0	0/2	1/2	1/1	2/2
14	A	32	2	4/4	0/0	0/0	0/0	0/0	1/2	1/2	0/0	0/0
	M	43	2	4/4	0/0	0/0	0/0	0/0	1/2	1/2	0/0	0/0
15	A	66	3	5/5	4/4	0/0	0/0	0/0	2/2	1/2	0/0	0/0
	M	82	3	5/5	4/4	0/0	0/0	0/0	1/2	1/2	0/0	0/0
16	A	836	9	13/14	24/26	0/0	1/1	2/2	3/3	0/2	0/0	2/2
	M	847	8	14/14	26/26	0/0	1/1	2/2	2/3	0/2	0/0	2/2
17	A	215	5	8/8	2/2	0/0	0/1	2/2	2/2	0/2	0/0	0/4
	M	220	5	8/8	2/2	0/0	1/1	2/2	1/2	0/2	0/0	0/4
18	A	268	5	6/6	6/6	0/0	0/1	2/2	2/2	0/2	1/1	2/4
	M	268	5	6/6	6/6	0/0	0/1	2/2	2/2	0/2	1/1	3/4
19	A	1590	5	10/10	44/44	0/0	0/2	2/2	1/1	1/2	0/0	4/4
	M	1494	5	10/10	44/44	0/0	0/2	0/2	1/1	2/2	0/0	4/4
20	A	174	5	6/10	23/23	0/0	0/0	0/0	3/4	1/2	0/0	4/4
	M	230	8	10/10	23/23	0/0	0/0	0/0	2/4	2/2	0/0	4/4
21	A	131	5	9/10	2/2	0/0	0/0	0/0	2/2	3/3	0/0	0/0
	M	131	5	9/10	2/2	0/0	0/0	0/0	2/2	3/3	0/0	0/0

Appendix I: Post Analysis Comparisons

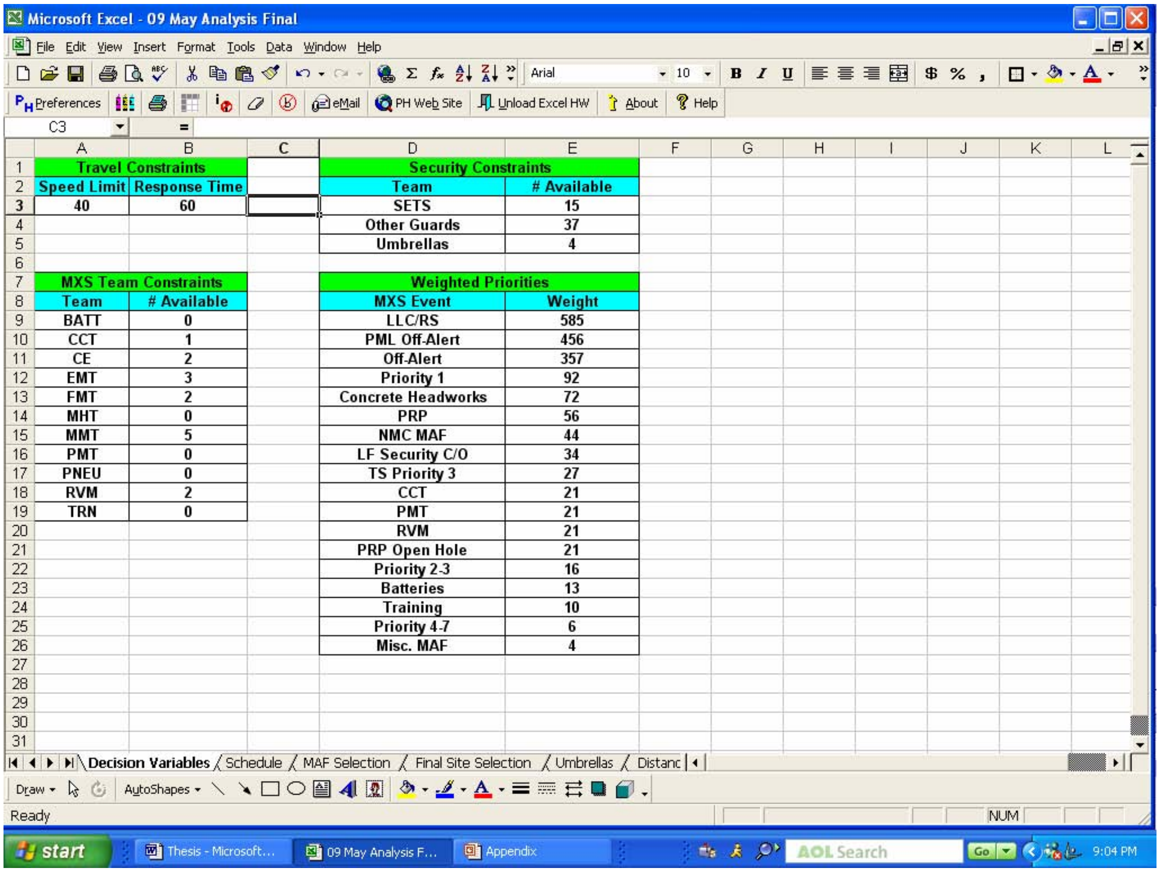
May		PMT	PNEU	RVM	TRN	LFs
1	A	0/0	1/1	2/2	0/0	B04,C03,C05,C06,G07,H02,H08,N03,
	M	0/0	1/1	2/2	0/0	B04,C03,C05,C06,E04,G07,H02,L08
2	A	0/0	0/0	2/2	0/0	A09,C03,C05,E03,G07,H08,M09,N03,N04
	M	0/0	0/0	2/2	0/0	C03,C05,E03,G07,H08,L08,M09,N03,N04
3	A	3/3	0/0	2/3	1/2	B05,C05,E04,F02,H10,I03,N03,N04
	M	2/3	0/0	2/3	1/2	C03,C05,E03,E04,F02,F04,G07,H08,N03,N04
4	A	3/3	1/1	1/1	0/0	C03,C05,C06,E03,F04,G07,G11,I03,N03,N04
	M	3/3	0/1	1/1	0/0	C03,C05,E03,F04,G07,G11,H08,L08,M09,N03,N04
5	A	2/3	0/0	1/2	1/2	A11,B08,C04,C08,G07,I03,M09,M03,N04
	M	2/3	0/0	2/2	0/2	C04,C08,F10,G07,H08,I03,L08,M09,N03,N04
6	A	1/1	0/1	0/0	1/1	B04,B10,C05,C11,F04,H09
	M	1/1	0/1	0/0	1/1	B04,C05,C11,F04,I02,J04
7	A	0/0	0/0	0/0	0/0	B04,F07,I02,M09
	M	0/0	0/0	0/0	0/0	B04,F07,F10,I02
8	A	0/0	0/0	0/0	0/0	B04
	M	0/0	0/0	0/0	0/0	B04
9	A	0/0	0/0	2/2	0/0	A04,E04,F10,I03,J04,M09,N05,N06
	M	0/0	0/0	2/2	0/0	E04,F10,G07,H08,J04,L08,M09,N05,N06
10	A	0/1	0/0	0/1	0/0	H08,N05,N06
	M	0/1	0/0	0/1	0/0	H08,N05,N06
11	A	0/0	0/0	2/2	0/0	H04,I03,M09,N05,N06
	M	0/0	0/0	1/2	0/0	A06,B04,M09,N05,N06
12	A	0/0	0/0	2/2	0/0	B04,I03,J09,N05,N06
	M	0/0	0/0	2/2	0/0	E04,G07,I03,M09,N05,N06
13	A	0/0	1/1	0/0	0/0	B10,E08,G07
	M	0/0	0/1	0/0	0/0	A06,B04,G07
14	A	0/0	0/0	0/0	0/0	F08,J11
	M	0/0	0/0	0/0	0/0	B04,E04
15	A	0/0	0/0	0/1	0/0	E04,J02,J11
	M	0/0	0/0	1/1	0/0	B04,I03,J02
16	A	2/2	0/0	1/2	1/1	A11,F05,F07,G07,J02,J09,M09,N02,N11
	M	2/2	0/0	2/2	0/1	F05,F07,I03,J02,J09,M09,N02,N11
17	A	0/3	0/0	1/2	0/1	H02,J07,K07,N02,N11
	M	1/3	0/0	1/2	0/1	F05,H02,M09,N02,N11
18	A	0/2	0/0	0/0	0/1	C10,J02,J09,N02,N11
	M	0/2	0/0	0/0	0/1	C10,J02,J09,N02,N11
19	A	0/1	0/0	0/3	0/0	B04,H05,H08,N02,N11
	M	1/1	0/0	0/3	0/0	B04,F05,F11,H05,H08
20	A	0/0	0/0	0/3	0/1	C10,G07,H02,J06,J07
	M	0/0	0/0	2/3	1/1	A11,B04,F05,G07,H02,I03,J07,J09
21	A	0/0	0/0	0/0	0/0	A09,B04,C04,C10,E04
	M	0/0	0/0	0/0	0/0	A09,B04,C04,C10,E04

Appendix I: Post Analysis Comparisons

May		Wt	LFs	SETS	Other	BATT	CCT	CE	EMT	FMT	MHT	MMT
22	A	216	8	15/16	0/0	0/0	1/1	0/0	2/2	2/2	0/0	0/0
	M	217	7	14/16	0/0	0/0	0/1	0/0	2/2	2/2	0/0	0/0
23	A	1325	8	14/14	37/37	0/0	1/1	0/0	3/3	2/2	0/0	4/4
	M	1304	7	13/14	37/37	0/0	0/1	0/0	3/3	1/2	0/0	4/4
24	A	137	7	12/12	0/0	0/0	1/2	0/0	0/1	1/3	0/0	0/0
	M	154	7	12/12	0/0	0/0	0/2	0/0	0/1	3/3	0/0	0/0
25	A	473	7	12/14	0/0	0/0	1/1	0/0	1/1	2/2	0/0	4/4
	M	495	7	14/14	0/0	0/0	1/1	0/0	1/1	2/2	0/0	4/4
26	A	797	4	7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4
	M	797	4	7/7	15/15	0/0	0/1	0/0	2/2	1/2	1/1	4/4

May		PMT	PNEU	RVM	TRN	LFs
22	A	0/0	0/0	3/3	0/0	G07,H09,I03,I04,J09,K04,K07,M09
	M	0/0	0/0	3/3	0/0	A09,B04,G07,I03,I04,J09,K07
23	A	0/1	0/0	3/3	0/0	B04,G05,G07,I03,I04,J09,K07,M09
	M	0/1	0/0	3/3	0/0	A09,G05,G07,I03,I04,J09,K07
24	A	0/0	0/0	4/4	0/0	A09,E04,I03,J09,K02,K07,M09
	M	0/0	0/0	3/4	1/1	A09,A11,C07,I03,J08,J09,K07
25	A	0/0	0/0	2/2	1/1	C07,I03,J09,K07,K11,M09
	M	0/0	0/0	1/2	1/1	A06,A11,C07,J08,J09,K07,K11
26	A	0/0	0/0	0/1	0/0	J08,K09,L04,M09
	M	0/0	0/0	0/1	0/0	J08,K09,L04,M09

Appendix J: Screenshot of Research Model: Constraints/Weights



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Travel Constraints	
Speed Limit	Response Time
40	60

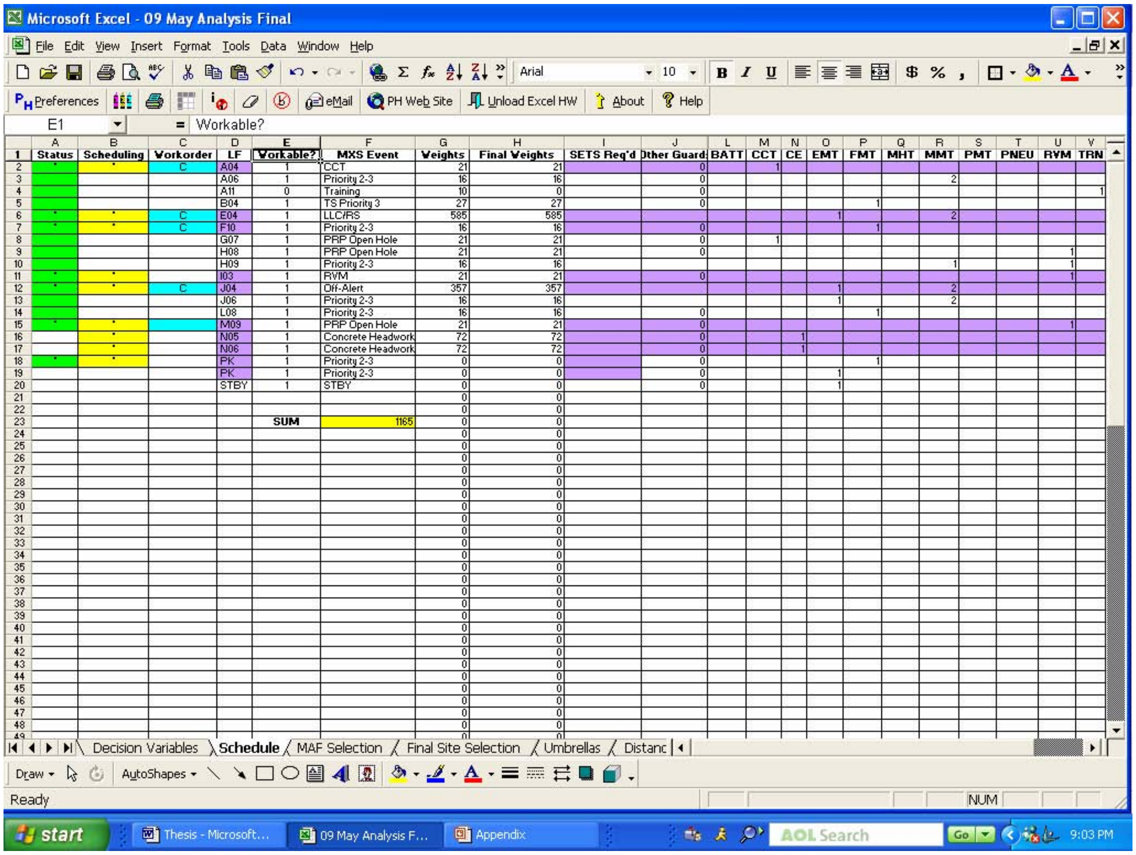
Security Constraints	
Team	# Available
SETS	15
Other Guards	37
Umbrellas	4

MXS Team Constraints	
Team	# Available
BATT	0
CCT	1
CE	2
EMT	3
FMT	2
MHT	0
MMT	5
PMT	0
PNEU	0
RVM	2
TRN	0

Weighted Priorities	
MXS Event	Weight
LLC/RS	585
PML Off-Alert	456
Off-Alert	357
Priority 1	92
Concrete Headworks	72
PRP	56
NMC MAF	44
LF Security C/O	34
TS Priority 3	27
CCT	21
PMT	21
RVM	21
PRP Open Hole	21
Priority 2-3	16
Batteries	13
Training	10
Priority 4-7	6
Misc. MAF	4

Decision Variables / Schedule / MAF Selection / Final Site Selection / Umbrellas / Distanc

Appendix K: Screenshot of Research Model: Actual Maintenance Schedule



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E1 = Workable?

	A	B	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R	S	T	U	V
1	Status	Scheduling	Workorder	LF	Workable?	MXS Event	Weights	Final Weights	SETS Req'd	Other Guard	BATT	CCT	CE	EMT	FMT	MHT	MMT	PMT	PNEU	RVM	TRN
2	•	•	C	A04	1	CCT	21	21		0		1									
3				A06	1	Priority 2-3	16	16		0							2				
4				A11	0	Training	10	0		0											1
5				B04	1	TS Priority 3	27	27		0					1						
6	•	•	C	E04	1	LLC/RS	585	585						1			2				
7	•	•	C	F10	1	Priority 2-3	16	16		0					1						
8				G07	1	PRP Open Hole	21	21		0		1									
9				H08	1	PRP Open Hole	21	21		0										1	
10				H09	1	Priority 2-3	16	16									1			1	
11	•	•		I03	1	RVM	21	21		0										1	
12	•	•	C	J04	1	Off-Alert	357	357						1			2				
13				J06	1	Priority 2-3	16	16						1			2				
14				L08	1	Priority 2-3	16	16		0					1						
15	•	•		M09	1	PRP Open Hole	21	21		0										1	
16		•		N05	1	Concrete Headwork	72	72		0			1								
17		•		N06	1	Concrete Headwork	72	72		0			1								
18	•	•		PK	1	Priority 2-3	0	0		0					1						
19				PK	1	Priority 2-3	0	0		0				1							
20				STBY	1	STBY	0	0		0				1							
21							0	0													
22							0	0													
23					SUM	1165	0	0													
24							0	0													
25							0	0													
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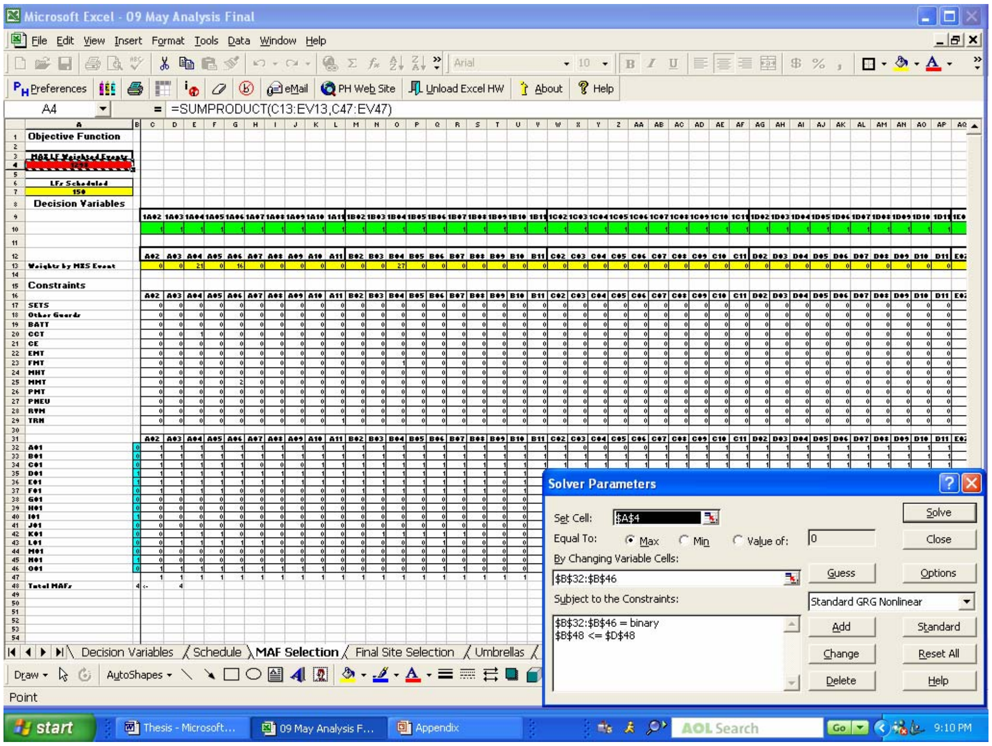
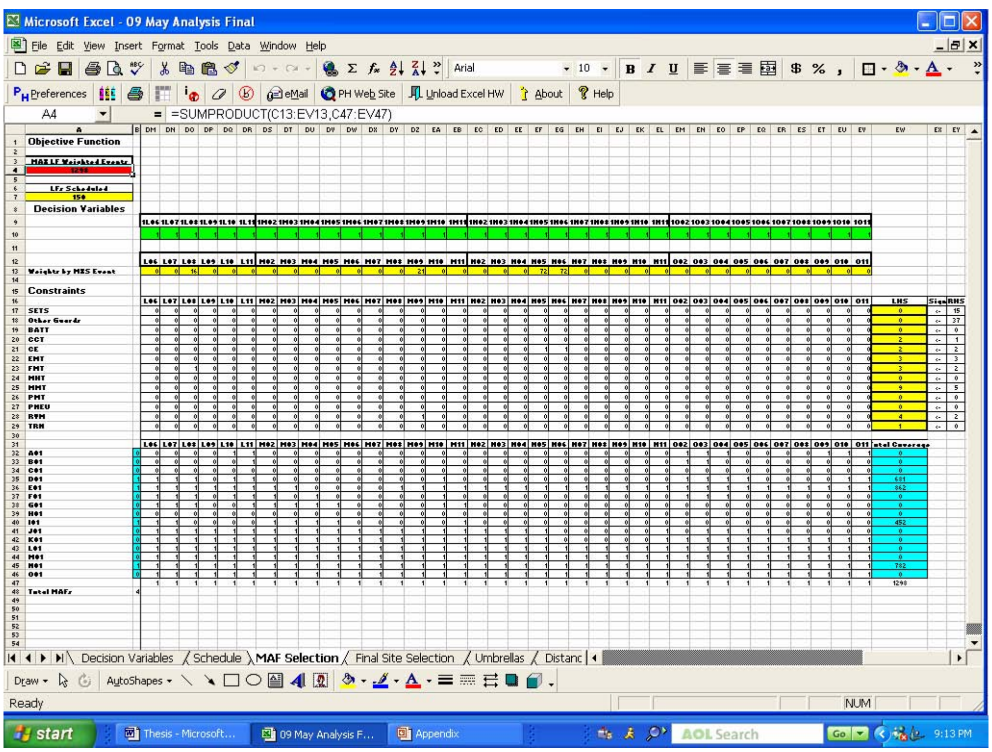
48							0	0													

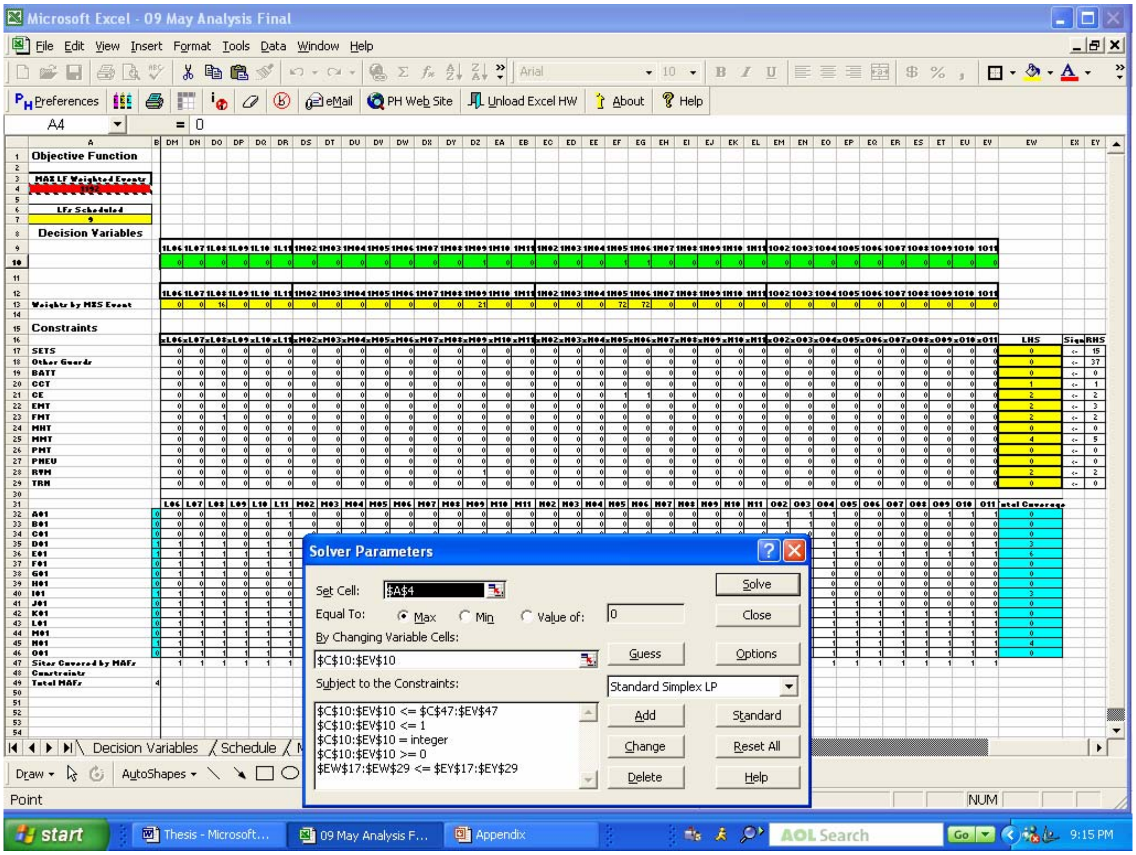
Decision Variables / Schedule / MAF Selection / Final Site Selection / Umbrellas / Distanc

Appendix L: Screenshot of Research Model: Model Stage One





Appendix M: Screenshot of Research Model: Model Stage Two



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Vita

Captain Dale L Overholts II graduated from McDowell High School, Erie, Pennsylvania, in June 1990. He enlisted in 1992 as a Precision Measurement Equipment Laboratory (PMEL) Technician, attaining the rank of staff sergeant during a 7-year enlisted career, with assignments at McGuire AFB, New Jersey, and Ramstein AB, Germany. He earned honors as the Air Force Lt Gen Leo Marquez Award recipient, Aircraft Maintenance Technician category, 1994; the Twelve Outstanding Airmen of the Air Force, 1995; and the 86th Airlift Wing Airman of the Year, 1997. He was the John L. Levitow Award recipient for his Airman Leadership School class.

Captain Overholts graduated *Cum Laude* with a Bachelor of Science degree in Workforce Education and Development from Southern Illinois University in 1997. He was commissioned through Officer Training School in 1999 and was a Distinguished Graduate. After commissioning, Captain Overholts attended the Missile Maintenance Officer Course at Vandenberg AFB, California.

In May 1999, he was assigned to Malmstrom AFB, Montana. In October 2000, Captain Overholts was assigned to Francis E. Warren AFB, WY, where he served in the 90th Logistics Support Squadron, 90th Maintenance Squadron, and Headquarters 20th Air Force. Since commissioning, he has received the Best Contributor Award from Aerospace Basic Course, Top-Third Graduate from Squadron Officers School, and various unit-level awards. In August 2004, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the 576th Flight Test Squadron at Vandenberg AFB, California. Captain Overholts is married and has two sons.

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14. ABSTRACT

The events of September 11, 2001 have led to increased security requirements for all ICBM-related activities. Missile maintenance managers must explore new scheduling techniques to sustain weapon system readiness levels in light of published security enhancements. The problem of improving missile maintenance scheduling is modeled as a two-stage heuristic that utilizes the maximal covering location problem methodology. Maintenance activities are categorized and weighted according to published priority designation and mission impact. The model's first stage seeks to select two security umbrellas that maximize the weighted sum of maintenance activities. Stage two seeks to determine a maintenance schedule comprised of launch facilities covered by the stage one security umbrellas. Model constraints include number of security umbrellas, security force response times, and maintenance and security personnel availability. Scheduling effectiveness is determined by comparing research model solutions to actual maintenance activities accomplished at F. E. Warren AFB, WY during May 2005. Sensitivity analysis is used to demonstrate the effects of adjusting security force response times and security umbrella quantity constraints on maintenance activities performed and manpower utilization. Missile maintenance and security forces managers can use this information to determine feasible schedules that fulfill prescribed security requirements, while sustaining current weapon system readiness levels.

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